Water and Benefit Sharing in Transboundary River Basins

Thèse

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Résumé

Le partage équitable des bénéfices dans les bassins fluviaux transfrontaliers est nécessaire pour résoudre les conflits entre les pays riverains et atteindre un consensus sur les activités de développement et de gestion du bassin versant. Le partage des bénéfices doit être discuté collectivement par tous les pays riverains pour être perçu non seulement comme efficace, mais aussi équitable. La littérature actuelle décrit principalement ce que l'on entend par le partage des bénéfices d'un point de vue conceptuel. Les arrangements institutionnels pratiques qui assurent le bien-être économique maximal, ainsi que les méthodes développées en collaboration pour encourager le partage équitable des bénéfices, ne sont toutefois pas présentés.

L'objectif global de ce projet de thèse est de développer un arrangement institutionnel, qui comprend à la fois des politiques de répartition de l'eau et des mécanismes de partage des bénéfices, afin d'améliorer la gestion des ressources en eau transfrontalières et d'encourager la coopération entre les pays riverains. La méthodologie étend l'approche traditionnelle, basée sur des stratégies d'allocation très limitées en allouant efficacement les ressources en eau et le partage équitable des bénéfices découlant de l'utilisation de l'eau.

Cette thèse détaille l'arrangement institutionnel développé et, à travers trois activités distinctes, les principales composantes de l'arrangement sont analysés. Dans l'arrangement institutionnel, une autorité de bassin fluvial (RBA) est l'opérateur d'un système axé sur le marché, dans lequel les politiques d'allocation économiquement efficaces sont identifiées et imposées aux usagers de l'eau, qui doit payer pour l'eau qui leur est alloué. Ces frais sont collectés et redistribués, via une règle de partage spécifique au bassin fluvial, afin d'assurer l'équité entre les usagers de l'eau.

Le bassin du Nil oriental est utilisé comme étude de cas pour illustrer l'approche. Il y a des secteurs hydroélectriques et agricoles répartis dans trois pays (Egypte, Soudan et Ethiopie) et une longue histoire de non-coopération dans ce bassin. La répartition actuelle de l'eau repose sur des accords bilatéraux de l'époque coloniale, qui désignent l'Egypte et le Soudan comme les seuls bénéficiaires des eaux du Nil. La coopération future est impérative dans ce bassin pour profiter du potentiel hydroélectrique en Ethiopie, et du potentiel de l'agriculture au Soudan, ainsi que pour atténuer, autant que possible, les effets du changement climatique.

Les résultats montrent que la gestion coopérative du bassin du Nil oriental, et de son infrastructure, augmenterait considérablement les bénéfices économiques à l'échelle du bassin et entraînerait une répartition de l'eau plus efficace. L'arrangement institutionnel garantit que l'eau est retirée ouù elle a la plus grande valeur et que les investissements en amont dans des projets à faible productivité sont découragés. Le plus haut niveau de coopération est effectuée en vertu d'une institution supranationale et toutes les parties doivent se mettre d'accord sur la définition de l'équité dans le le partage des bénéfices. L'imposition d'axiomes spécifiques sur la base de cette vision collaborative de l'équité se traduit par une solution unique pour la répartition des bénéfices économiques. Une règle de partage élaborée avec la participation des parties prenantes peut être plus acceptable parce que la définition de la règle n'est pas contestée, comme ce serait le cas si les règles existantes avaientété appliquées avec leurs propres définitions de l'équité.

Enfin, les résultats globaux montrent que la réalisation de compromis entre l'efficacité et l'équité peut se produire lorsque ces deux principes de répartition de l'eau sont couplés afin de maximiser les avantages de l'utilisation de l'eau, puis de réaffecter ces d'une manière équitable.

Abstract

The equitable sharing of benefits in transboundary river basins is necessary to solve disputes among riparian countries and to reach a consensus on basin-wide development and management activities. Benefit-sharing arrangements must be collaboratively developed to be perceived not only as efficient, but also as equitable, and to be considered acceptable to all riparian countries. The current literature mainly describes what is meant by the term benefit sharing, in the context of transboundary river basins, and discusses this from a conceptual point of view. Practical, institutional arrangements that ensure maximum economic welfare, as well as collaboratively developed methods for encouraging the equitable sharing of benefits, are, however, not provided.

The overall objective of this PhD project was to develop an institutional arrangement, that includes both water allocation policies and benefit-sharing mechanisms, to improve the sustainability of managing transboundary water resources and to encourage cooperation between riparian states. The methodology extends the traditional approach, which is based on highly constrained allocation policies, that merely complement existing management institutions, by efficiently allocating water resources and then equitably sharing the benefits derived from water use.

This thesis details the institutional arrangement developed and, through three separate activities, the main components of the arrangement are analyzed. A river basin authority (RBA) is the operator of a market-based system, in which economically efficient allocation policies are identified and imposed on water users, who are charged for the water allocated to them. These charges are collected and redistributed, via a sharing rule specific to the river basin, to ensure equity among the water users.

The Eastern Nile River Basin is used as the case study to illustrate the approach. There are important hydropower and agricultural sectors spread across three countries (Egypt, Sudan and Ethiopia), and there is a long history of non-cooperation in this river basin. Current water allocation is based on colonial era bilateral agreements that designate Egypt and Sudan as the only beneficiaries of the Nile waters. Future cooperation is imperative, in this basin, to take advantage of hydropower potential in Ethiopia, and agriculture potential in Sudan, as well as to mitigate, as much as possible, the effects of climate change in the near future.

Results reveal that the cooperative management of the Eastern Nile River Basin and its infrastructure would significantly increase the basin-wide economic benefits and lead to more efficient water allocation. The institutional arrangement ensures that water is withdrawn where it has the greatest value (efficient water allocation is established) and that upstream investments in low productivity projects are discouraged. The highest level of cooperation is effectuated through a supranational institution and all parties must agree on the definition of fairness in the sharing of benefits.The imposition of specific axioms, based on this agreed-upon vision of fairness results in a unique solution for the distribution of economic benefits. A sharing rule developed with stakeholder input may be more acceptable because the definition of the rule is not in question, as would be the case if existing rules were applied with their inherent definitions of equity.

Finally, overall results show that achieving trade-offs between efficiency and equity can occur when these two principles of water allocation are coupled to first maximize the benefits from water use and then reallocate these in an equitable manner.

Contents

List of Tables

List of Figures

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Avant-propos

This PhD thesis is based on research carried out between June 2012 and March 2016 at the Department of Civil and Water Engineering, Laval University, under the supervision of Professor Amaury Tilmant.

The main part of this thesis consists of the introduction and four chapters which provide a synopsis summarizing the main findings of three activities that were undertaken as part of this PhD project, followed by conclusions.

Each of the three activities were the subject of scientific articles on which I am the first author. These articles are found in Appendix A. Two of these have been published and one has been submitted for publication (as detailed below). As well, two articles, on which I am second author, have been included in Appendix B.

Paper I: D. Arjoon [1], Y. Mohamed [2], Q. Goor [3] and A. Tilmant [4]. 2014. Hydro-economic risk assessment in the Eastern Nile River basin. Water Resources and Economics, 8, 16-31 (Published November 2014).

Paper II: D. Arjoon, A. Tilmant and M. Herrmann [5]. 2016. Sharing water and benefits in transboundary river basins. Hydrology and Earth System Sciences, 20, 2135-2150. (Published June 2016).

Paper III: D. Arjoon and A. Tilmant. 2016. Bankruptcy rules and benefit sharing in transboundary river basins. Submitted to Water Resources Management. (Submitted October 2016).

Supplementary paper I: A. Tilmant, D. Arjoon and G. Fernandes Marques [6]. 2014. Economic Value of Storage in Multireservoir Systems. Journal of Water Resources Planning and Management, 140(3), 375-383.

Supplementary paper II: T.N. Kahsay [7], D. Arjoon, O. Kuik [8], R. Brouwer [9], A. Tilmant and P. van der Zaag [10]. 2016. Combining a partial and general equilibrium modeling approach to assess the economic impacts of the Grand Ethiopian Renaissance Dam on the Eastern Nile economies. In Preparation.

In each of the papers in which I was first author, I carried out the research, performed the analysis, wrote the text and, in the case of published articles, wrote the responses to the reviewers. The co-authors, in each case, provided invaluable support which consisted of offering guidance and advice with respect to the analysis of results and the review process and reading and correcting the drafts.

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Introduction

Natural resources are economically, socially and environmentally important in ensuring healthy living conditions and ecosystems. Our dependence on water, in particular, to meet our basic needs and to support an ever increasing standard of living, along with the necessity of water to sustain our planet's fragile ecosystems, makes it unique among natural resources. Despite its importance, or more perhaps because of it, one third of the world is facing water shortages. It is a general belief that the current and predicted water crisis is due to soaring water demands and a decrease in supply. It is becoming evident, however, that generally poor management of the available resource is exacerbating the problem. It can be argued that, rather than being in the midst of a water availability crisis, we have a water management crisis, and that creative policy reforms will allow us to obtain much more from our current resources (Zilberman et al., 1993). Until recently, the focus in water resource management has been on the allocation of the physical resource, itself, to competing uses. Increasing pressures such as population and economic growth, increased demand for food and energy, and increased climate variability are leading to a perceived shortage of water to satisfy all uses. Within the boundaries of a nation, the problems of responding to these pressures are large, however, in the case of water resources that are shared between countries (transboundary or international water resources) the problem is even more challenging due to the additional, fragmented, political layer and the presence of unidirectional (non-reciprocated) externalities.

There are more than 250 rivers around the world that cross the boundaries of two or more countries. Statistics taken from Wolfe (2009) show that the basins of these rivers make up approximately 47% of the earth's land surface, include 40% of the world's population and contribute almost 60% of freshwater flow. Of these countries, 21% of these lie entirely within an international basin and, including these 21%, 33 countries have over 95% of their territories within these basins. Nineteen international river basins are shared by five or more riparian countries (Figure 0.1).

In the absence of binding mechanisms, the harmonious management and development of international river basins is left to the goodwill of riparian countries. However, in the context of resource scarcity, this goodwill may be buffeted by the fear of entering a zero sum game. To circumvent the problems inherent in this perception, some authors have suggested that the

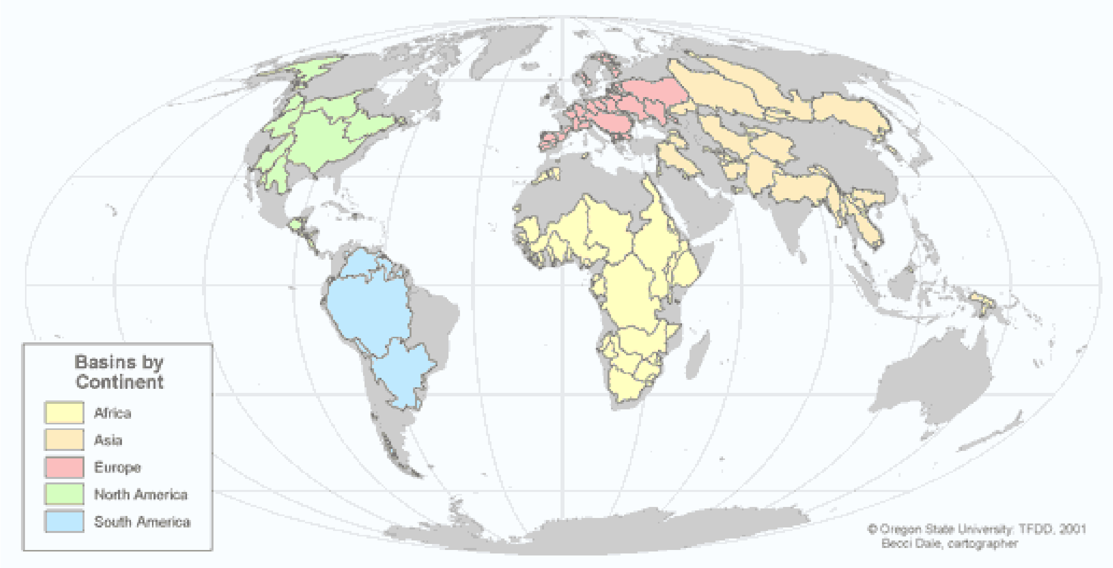

Figure 0.1: International river basins as delineated by the Transboundary Freshwater Dispute Database project, Oregon State University, 2000. Data source: International River Basins, Wolf et al. (1999), updated 2001.

problem of water sharing in international basins be considered in terms of the benefits related to water use, rather than on the allocation of water itself (Biswas, 1999; Sadoff and Grey, 2002). The idea is to transform a zero-sum game of water sharing into a positive sum game through the equitable sharing of benefits based on mutual agreements. This strategy requires that the entire river basin be managed as a unit, regardless of the number of countries that the river flows through, and that efficient policy frameworks be developed and accepted by all nations involved. It is by developing water resources at the basin scale that synergies can be identified, that negative impacts can be mitigated, and that profits can be maximized.

The road towards the implementation of benefit sharing arrangements, however, is fraught with difficulties. For many countries, for example, the short-term strategy is to pursue a *fait accompli* tactic by developing water resources as soon as possible in order to be in a stronger position at the negotiating table. Another difficulty is to put a value on cooperation, especially when different types of benefits (economic, ecological, social, cultural, etc.), as well as positive and negative externalities associated with various types of water uses, must be considered (Alam, Dione and Jeffrey, 2009). Finally, it is still unclear how the allocation of water and the allocation of benefits should be constructed, organized and eventually integrated.

0.1 Thesis objectives

The overall objective of this PhD project was to develop an innovative institutional arrangement that includes both water allocation policies and benefit-sharing mechanisms, to improve the sustainability of managing transboundary water resources. The project extends the traditional approach, which is based on highly constrained allocation policies that merely complement existing management institutions (Harou et al., 2009; Booker, Michelsen and Ward, 2005), by designing an institutional arrangement that not only allocates water resources efficiently, but also equitably shares the benefits derived from the efficient allocation policies, thereby encouraging cooperation.

The specific research questions guiding this PhD project are as follows:

In the case of closed transboundary river basins, where water resources are fully allocated and water demand exceeds water availability,

1. How would water allocation change with respect to different management and cooperation scenarios?
2. What institutional arrangement can be used to efficiently share water and equitably share the benefits of water use?
3. How does the sharing of benefits change with respect to the definition of fairness?

In an attempt to answer these questions, three individual activities were realized, using the Eastern Nile River Basin as the case study:

1. A hydro-economic model was used to evaluate the differences in water allocation policies that result from various cooperation and management arrangements in a river basin. Four different scenarios were analyzed including a baseline scenario, a scenario that assesses the effect of major upstream hydropower infrastructure on downstream riparians, a scenario based on possible irrigation expansion in a basin and a scenario in which the operation of major hydropower infrastructure is not coordinated over the basin. The details of this activity, and the results obtained, are found in **Paper I**.
2. An innovative market-based institutional arrangement, in which water is efficiently allocated across a transboundary river basin, and the benefits of the resulting water use are equitably shared, is presented in **Paper II**. In this activity, a future scenario is imagined in which a large upstream infrastructure, that does not currently exist, is online and consumptive water use has increased upstream in the basin. As well, a supranational river basin authority (RBA) exists and there is full cooperation between water users in the basin.
3. The results obtained from applying a rule developed for sharing the benefits of cooperation in **Activity #2**, which is based on bankruptcy methods, is compared to the results of applying three common bankruptcy sharing rules to the same problem. This activity, and the results found, are described in detail in **Paper III**.

0.2 Thesis Outline

The main part of this thesis presents a synopsis that summarizes the findings of the three activities undertaken as part of the PhD project. The first chapter is a literature review which provides a context for the work and introduces the main concepts presented in subsequent chapters. Chapter 2 provides a description of the methods that were used to accomplish the activities. Chapter 3 presents a detailed description of the Eastern Nile River basin, the case study on which the methodologies, developed in each activity, are applied. Finally, Chapter 4 is an extended summary of the results of the three activities, along with a cohesive analysis and general discussion that links the results. The synopsis is followed by the appendices and the bibliography.

Chapter 1

Literature Review

This chapter provides an overview of the current literature in the fields of water and benefit sharing in transboundary river basins. In the first section of this chapter (1.1), after a review of the general problem of water scarcity, the principles of water allocation and the laws governing water allocation in transboundary river basins are discussed, followed by an overview of the concept of benefit sharing in transboundary river basins. In Section 1.2, current literature on modelling water allocation and benefit sharing, in the context of transboundary river basins, is reviewed.

1.1 Overview of the Problem

1.1.1 Water scarcity

Water scarcity, in it's simplest form, involves an imbalance between water demand and supply. The use of water has grown at more than twice the rate of the global population over the last century (FAO, 2012) and recent issues, such as ecosystem degradation, are forcing a reevaluation of the way this resource is used. On the supply side, pollution and climate change are two main concerns. The perception that water is becoming scarce as a result of these trends has led many to conclude that a water scarcity crisis is inevitable. "Yet, the more predictable challenges (or potential crisis) can be largely avoided by adjusting the way in which water is managed and governed" (Moriarty, Butterworth and Batchelor, 2004). In this section, the main water demand and supply drivers are briefly reviewed, followed by a discussion on water scarcity.

Water demand

According to the United Nations, the world population will level off at 9.2 billion people in 2050, with most of this growth being absorbed by less developed regions (United Nations Department of Economic and Social Affairs, 2006). This population increase, along with the current trend of increased living standards in developed and developing nations, has resulted in an increase in demand for water in the agricultural, energy, domestic and industrial sectors.

Over the same period, food demand is predicted to increase by 70% (Bruinsma, 2009). Current estimates indicate that 80% of the additional food supplies required to feed the future world population will depend on the availability of a reliable water supply for irrigation (Biswas, 2007). In the energy sector there is an expected 160% increase in demand over the next three decades (Steer, 2010). This will make hydropower an increasingly important use of water. In fact, the increased demand for hydropower is already being felt, with developing countries in Asia doubling their total hydropower generating capacity between 1990 and 2000 (Biswas, 2007).

With the increasing demand for food and energy, and the resulting increase in water demand, the interdependence between sectors is increasing, and a strong understanding of these connections (referred to as the water-energy-food nexus) is required to ensure security in each of the sectors for a growing global population. Any strategy that focuses on one part of this nexus, without considering the interconnections, risks profound economic, environmental and social implications (Bizikova et al., 2013; FAO, 2014; Rasul and Sharma, 2015).

A relatively new demand-side driver is the need to maintain the environment that supports human needs by ensuring the benefits of a healthy ecosystem. These benefits, such as nutrient recycling, climate regulation, flood and drought regulation, tourism and recreation, groundwater recharge, water purification and preservation of diversity, are commonly referred to as "ecosystem services". Studies on the value of allocating water to ecosystem services have increased (Costanza et al., 2008; Worldwatch Institute, 2007; World Water Assessment Programme, 2012) and ecosystem services are estimated to be worth trillions of dollars on an annual basis (Costanza et al., 2014).

Water supply

As the world demand for freshwater resources continues to grow, the supply of usable water is being affected mainly by climate change and increased contamination. Climate change, however, is the only supply-side driver that ultimately determines the amount of water that will actually be available (World Water Assessment Programme, 2009).

Managing water is also about managing its naturally occurring variability. Climate change threatens to make this variability greater by shifting and intensifying the extremes and by altering the timing, magnitude and duration of precipitation events leading to changes in precipitation patterns, which may result in some regions receiving too little rain and others receiving too much, and making precipitation less dependable and more erratic. The Stockholm Environment Institute estimates that, based on only moderate climate change, the proportion of the world's population living in countries of significant water stress will increase from approximately 34% (in 1995) to 63% by 2050 (Simms, Magrath and Reid, 2004). In Africa's large catchment basins of Niger, Lake Chad and Senegal, the total available water has already decreased by 40-60 percent, due to changing precipitation patterns, and desertification has been aggravated by lower than average annual rainfall, runoff and soil moisture, especially in northern, southern and western Africa (United Nations Environment Programme, 2002).

Water contamination affects the proportion of available water that is usable. Polluted water that cannot be used for drinking, bathing, industry or agriculture may effectively reduce the amount of water available for use in a given area (United Nations Environment Programme, 2010). For example, a 2008 report on the Yellow River argued that severe pollution caused by factory discharges and sewage from fast-expanding cities has made one-third of the river unusable, even for agricultural or industrial use (Branigan, 2008).

Water scarcity

The United Nations defines "water scarcity" as "the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be fully satisfied" (United Nations, 2007).

Based on the Falkenmark indicator, there are currently around 700 million people in 43 countries suffering from water scarcity, with sub-saharan Africa having the largest number of water stressed countries of any region. By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water stress conditions. With the existing climate change scenario, almost half of the world's population will be living in areas of high water stress by 2030, including between 75 million and 250 million people in Africa. Additionally, water scarcity in some arid and semi-arid places will displace between 24 and 700 million people (United Nations, 2005). Figure 1.1 shows the state of global water scarcity in 2000 and in 2050.

Water scarcity can also be defined on an economic basis (Figure 1.2). Economic water scarcity occurs in regions that have adequate water reserves, but where poor governance and infrastructure prevent it from being fully usable or where inefficient use and mismanagement of water resources leads to waste and contamination. Economic water scarcity can be alleviated through better governance and infrastructure investment, but physical water scarcity is projected to grow steadily as a result of the combined impacts of climate change and population growth.

While it is generally accepted that water scarcity is a result of increased demand and decreased supply, there is a belief that water scarcity has little to do with water availability. Instead, there is growing consensus that the water crisis problem is one of poor resource management. Cosgrove and Rijsberman (2000) state that "There is a water crisis today. But the crisis is not

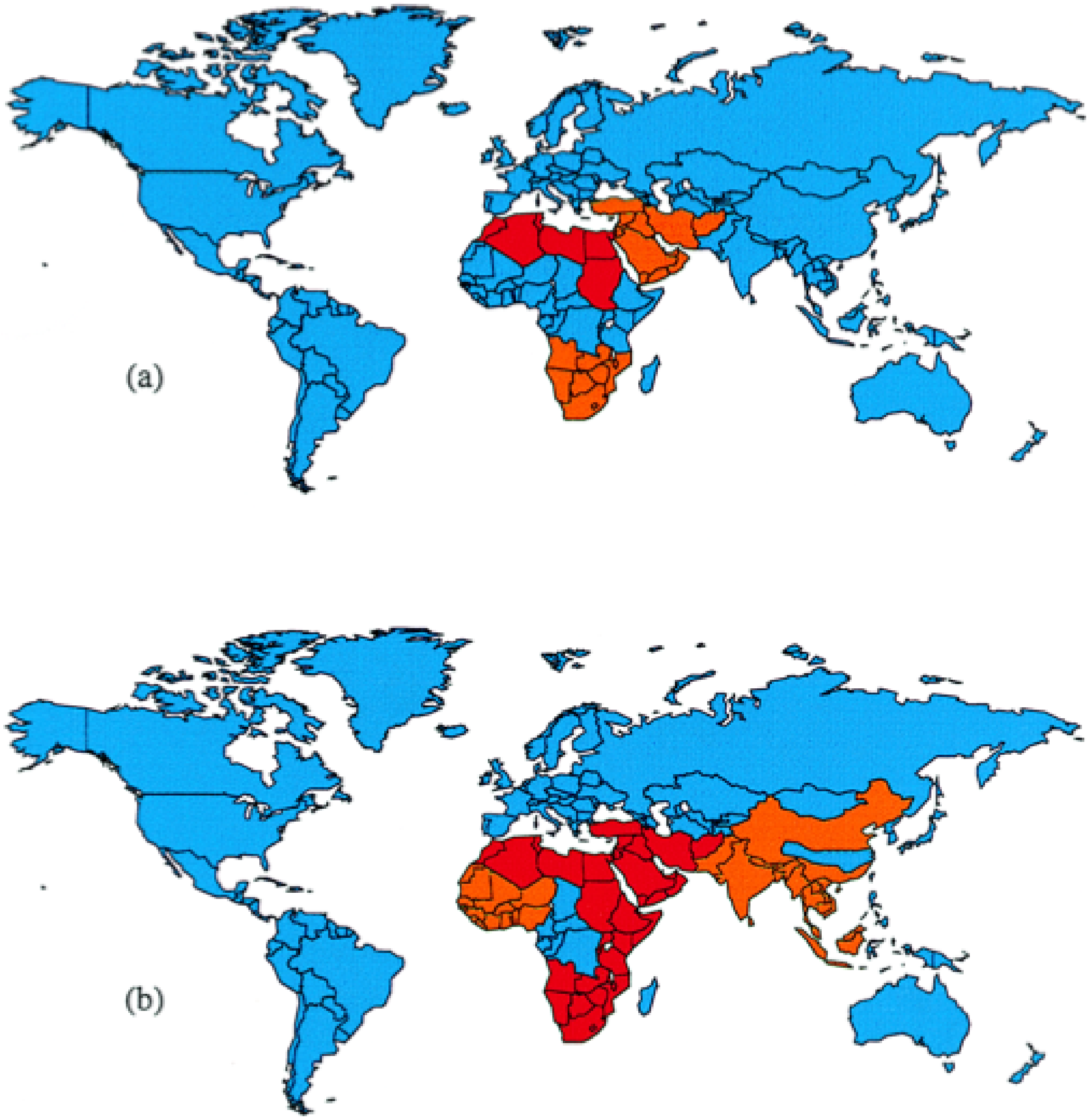

Figure 1.1: Global water scarcity (a) in 2000 and (b) in 2050. Regions are coded according to their per capita annual renewable freshwater resource. Red-less than 1000 m^3 per person per year, orange-between 1000 and 2000 m^3per person per year and blue-greater than 2000 m^3 per person per year (source: Wallace (2000))

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about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people - and the environment - suffer badly." Natural water scarcity, due to climate and hydrological processes, is aggravated by poor water management which leads to inadequate water allocation in space and time (Pereira, Cordery and Iacovides, 2009). Water management processes such as uncontrolled demand, inequity in water allocation, inappropriate irrigation

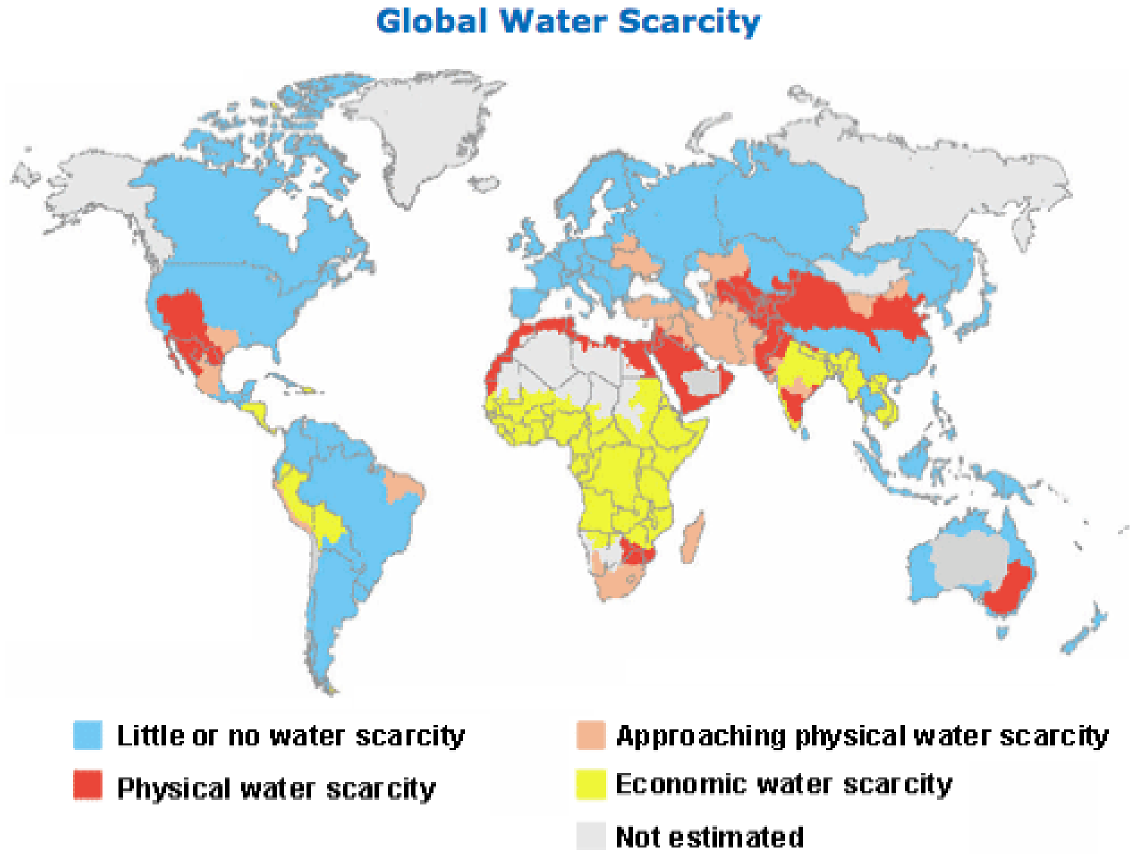


Figure 1.2: Global economic and physical water scarcity (source: International Water Management Institute (2006)).

practices, land misuse, poor infrastructure and poor management institutions all influence water scarcity. The need for effective water management is essential.

1.1.2 Water allocation

Water allocation is the central concept in the management of scarce water resources with the overall objective being to maximize the economic, social and environmental benefits of water to society (Wang, Fang and Hipel, 2003). In this section, the benefits of water and their corresponding principles of efficiency, equity and sustainability will be described, followed by a discussion of common water allocation mechanisms.

Principles of water allocation

The concept of *efficiency* is a view of water allocation from an economic perspective with the outcome being to maximize the economic benefits of water to society. This is a definition that is widely accepted by water resource managers.

The increased demand for water, and resulting increase in competition between water sectors, means that Pareto optimal trade-off solutions between sectors must be found. A precondition to the attainment of economic water allocation efficiency is the equimarginal principle (Juana, 2008) which states that the marginal benefits of water, at a given location, should be the same for all users or sectors (Agudelo, 2001). This is also known as an arbitrage condition. In this context, economically efficient water allocation results when the benefits from using one additional unit of water in one sector (or for one user) is the same as for all sectors (or users). Once this is achieved, any redistribution of water can make no sector, or user, better-off without making another worse-off. The implication of this principle is that "resources should be allocated in such a way that all the users and consumers derive equal value in using additional units of the resource" (Juana, 2008). If this were not the case, society would benefit by allocating more water to the sector in which the benefits, or returns, are the highest.

A second definition, that is much more widely used in practice, is the Hicks-Kaldor definition of efficiency (Howe, Schurmeier and Jr., 1986). In the Pareto optimality definition nobody is allowed to be made worse off. In the Hicks-Kaldor definition, some may be made worse off, initially, as long as the returns for those who gain outweigh the losses of those who lose (Schilizzi and Black, 2007). This definition allows for benefit transfers to be made in such a way that nobody will end up worse off while those who gain will still gain something. This less strict definition of efficiency is usually applied in the practice of policy making.

Allocation mechanisms (see Section 1.1.3 below) seek to equilibrate economic efficiency with *equity*. Equity relates to the fairness of water allocation "across different economically diverse groups in the population of a country or water management area" (Juana, 2008). Equitable water management requires that all users have equal access to the benefits generated from the use of the resource (Department of Water Affairs and Forestry, 1998). In other words, water allocation should be concerned not only with deriving the maximum benefits from the use of the resource, but also with how acceptable the process of allocation is to the water users/sectors. In many cases, equity in the access to water is not compatible with the objective of economic efficiency.

The sustainable use of water resources is becoming an increasingly important aspect in the allocation of water from the perspective of society (Koundouri, 2005). Intergenerational equity and the critical nature of ecological services provided by water resources are just two rationales for considering sustainability. Additionally, the in situ value and public good nature of water resources should enter into water allocation decisions and, even though the benefits from the environment cannot always easily be assessed in monetary terms, they should be evaluated in the decision making processes.

1.1.3 Mechanisms of water allocation

Different forms of water allocation schemes exist that attempt to combine the efficient and equitable sharing of water. Four of these are marginal cost pricing, public allocation, water markets and user-based allocation mechanisms.

Marginal Cost Pricing

Marginal cost pricing (MCP) is an allocation strategy that equates the price of water with the marginal cost of supplying the last unit of water. This is considered an economically efficient, or socially optimal, allocation by maximizing the total value of production across all affected sectors of the economy . As well, MCP avoids the tendency to under-price water, which avoids the overuse of water in times of scarcity because prices would rise to reflect the relative scarcity of the resource.

One of the principle limitations of MCP is the difficulty in defining the marginal cost itself, due to difficulties in collecting sufficient information to correctly estimate and, subsequently, monitor benefits and costs (Tsur et al., 2004). MCP also tends to neglect equity issues in favour of economic efficiency. Historically, MCP has been difficult to implement, requiring volumetric monitoring which is costly and difficult of administer. Increasingly, however, river basins are being monitored, and the availability of information is expanding due to significant efforts and financial resources that are being devoted to the observation of water resources, such as the Surface Water Ocean Topography (SWOT) satellite mission, which is anticipated to launch in 2020, and the Sentinel-3 satellite mission. Additionally, the concepts underlying MCP are often poorly understood by policymakers and administrators. Finally, the information requirements for an efficient system of administered prices are demanding. Again, however, this data is becoming more available. For industrial users, including hydropower generation, market prices and production functions are often well characterized. Currently, as well, market prices, either national or international, can be observed, and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers. As a result of numerous disadvantages and difficulties in implementing MCP, few good examples of its application exist.

Public Water Allocation

A public or administrative water allocation strategy distributes water among different sectors of the economy, often through water permits that define water use rights or through administered water pricing schemes (Wang, 2005). The allocation rules of this mechanism may be based on historical facts (such as prior rights), on equitable shares in available water volumes (such as regulated riparian rights), on individual requirements, or even on political pressure. Three main points support the argument for administrative intervention in the allocation of water resources: it is difficult to treat water in the same way as most market goods, water is widely perceived as a public good, and large-scale water development is too expensive for the private sector.

Administrative water allocation often leads to inefficient water use and a failure to create incentives for water conservation and improved use efficiency. Slow response to changes in water demand is also evident.

Public water allocation is widely practiced, usually consisting of various pricing schemes, such as flat or fixed rates (Yerushalmi, 2012). These are simple to manage and easy for users to understand.

Water Markets

A market-based allocation of water may be referred to as an exchange of water-use rights. In a pure market-based allocation the demand for, and supply of, water dictates the quantities to be traded as well as the unit price of water in the market and water is reallocated from low to high marginal value uses, making this an efficient allocation mechanism (Juana, 2008).

Water markets provide several benefits for sellers, buyers and the environment. The seller has the opportunity (under certain conditions) to improve profitability. The buyer benefits from the increasing water availability encouraged by the market.

There are, however, several unique challenges in the design of a well-functioning water market. These include: measuring water, defining water rights when flows are variable, enforcing withdrawal rules, investing in conveyance systems, sale of water-for-cash by poor farmers, externality and third party effects, and environmental degradation. Others argue that water is public property and markets cannot work for raw water (Wang, 2005).

Water markets, although a relatively new concept in some countries, exist in some form in Australia, Spain, California, Chile, and India. Dellapenna (2000) maintains that water markets are rare in reality and there are no true free markets.

User-Based Allocation

User-based water allocation occurs through the collective management of water sources, supplying water for either collective or individual use (Turner et al., 2004). Examples include community wells, farmer-managed irrigation systems, and systems managed by water and sanitation associations. Established rights to water use, as well as an appropriate institutional framework that has the capacity and strength to determine and regulate use are necessary (Turner et al., 2004). Many factors affect the viability of organizations for water management but property rights are a critical factor.

The potential flexibility to adapt water delivery patterns to meet local needs is a major advantage of user-based water allocation. This is due to the fact that those directly involved in the use of the water have more information on local conditions (Qtaishat, 2013). User organizations are also able to take into account domestic needs such as watering animals and washing clothes, along with agricultural needs. This may result in improvements in output per unit of water, or in equity, or both. Additional advantages include administrative feasibility, sustainability and political acceptability.

In order for user-based allocation rules to operate, a very transparent institutional structure, which may not always be available, is required. Local user-based institutions may be limited in their effectiveness because all sectors of water use are not represented (for example industrial demand). Therefore, coordination between the various use sectors are required and this could work through federations of user groups.

1.1.4 Transboundary water allocation

As indicated in the previous section, allocating water is not a straightforward process. Sharing water in an international context is even more complicated. Whenever a river crosses national boundaries, its use by one country has an effect on other countries sharing the same basin. This fact led to early debates on conflict and cooperation on international rivers with some predicting rising water conflicts and potential wars (Starr, 1991; Gleick, 1993; Lowi, 1993; Homer-Dixon, 1994) while others have more recently suggested that water may serve as a catalyst for cooperation (Wolfe and Brooks, 2003; Turton, 2000).

Recent literature has shown that cooperation is more likely to occur than conflict (Iyob, 2010; Wolfe, 2007; Zeitoun and Mirumachi, 2008), and most agree that cooperation must happen in order to ensure the equitable sharing of water in a basin.

The international community has developed general rules and guidelines with respect to water management in international river basins, however, shared water resources remain without a universal treaty to regulate its use and protection although specific treaties to delineate water allocation between nations do exist.

In this section, international water law, with respect to water allocation in transboundary situations, is highlighted, followed by a brief discussion of the need for cooperation in international river basins.

Principles of international water law

Varying theories and principles have emerged in an attempt to define and delineate the rights of riparian states with respect to the use of shared water. These principles are: the Harmon Doctrine (absolute territorial sovereignty), absolute territorial integrity, limited territorial sovereignty/integrity and the community of co-riparian states in the waters of an international river.

The Harmon Doctrine, or the principle of *absolute territorial sovereignty* acknowledges that "a state is free to dispose, within its territory, of the waters of an international river in any manner it deems fit, without concern for the harm or adverse impact that such use may cause to other riparian states" (Salman and Salman, 2007). This doctrine asserts the rights of upstream nations to use and pollute rivers with no regard for the effect of their actions on downstream nations. For obvious reasons, Harmon's opinion is widely criticized and discredited.

The doctrine of *absolute territorial integrity* establishes the right of a riparian state to demand the continuation of the natural flow in an international river into its territory from upper riparians and imposes a duty on upstream states to not restrict the natural flow of water downstream. This principle limits the use of water by upstream states to a minimal amount and favours downstream riparians. Like the Harmon Doctrine, this principle has been criticized and is not recognized as part of contemporary international water law.

The principle of *limited territorial sovereignty* or *limited territorial integrity* accepts the principle of riparian rights - that every nation bordering a watercourse has a right to use the water flowing in its territory - but establishes a corresponding duty to ensure that this use does not harm the territory or interests of other riparian nations. This doctrine restricts both of the previous principles and asserts the equality of all riparians in the use of the waters of the international river.

This principle of a *Community of co-riparian states in the waters of an international river* states that "the entire river basin is an economic unit, and the rights over the waters of the entire river are vested in the collective body of the riparian states, or divided among them either by agreement or on the basis of proportionality" (Salman and Salman, 2007). This is an extension of the principle of limited territorial sovereignty/integrity, but goes beyond by vesting the rights over the river in a collective body.

This principle did not gain wide acceptance because riparian states believe that it forces them to reach an agreement. This is an ideal principle that "overlooks sovereignty and nationalism, and the competing demands of the different riparians" (Salman and Salman, 2007).

The theory of limited territorial sovereignty/integrity is the prevailing theory that has formed the basis of international water rights and obligations (McCaffrey, 2001). Working out the details, however, has proven to be a complex and challenging task.

International water law governing transboundary river basins

In 1997, the UN Convention on the Non-Navigational Uses of International Watercourses (UNWC) was adopted. This Convention emphasizes cooperation (Article 8) and aims to establish the two main principles of the equitable and reasonable utilization of international water (Article 5), which is based on the theory of limited territorial sovereignty and the obligation not to cause significant harm (Article 7). In basing the convention on these principles, the protection of both upstream and downstream riparian countries is of foremost importance. The Convention, however, does not define one principle as overriding the other, leaving it open to interpretation. In 2014 the convention entered into force after receiving its 35th ratifying signature (Vietnam). The convention provides a global legal framework and an overall international consensus on transboundary water governance. It acts as a foundation from which transboundary water agreements can build a legal framework. It also, importantly, establishes the duty of ratifying nations to share hydrological data and information and to notify other riparians of planned development.

Although a step in the right direction toward the governance of transboundary waters, numerous challenges continue to exist. Ratification of the convention took 17 years and support is particularly lagging in Asia (with only 2 nations, Uzbekistan and Vietnam, having ratified the treaty), North America and South America. Two of the most highly water-stressed regions of the world, India and China have not ratified the convention.

In general, the principles within the UNWC can be more effectively implemented in river basins in which cooperation between riparians is already advanced.

Cooperation in international river basins

Attempts at applying international water laws to ensure the harmonious allocation of water in transboundary river basins has resulted in a large number of international river agreements. Many of these, however, are bilateral in structure, even in those basins that include more than 2 riparian countries. For example, the Nile Water Agreement was negotiated only between Egypt and Sudan although there are eleven riparian countries on the Nile. A 1951 agreement on the Mekong River excluded Burma and China and a 1991 agreement on the management of the Ganges River included India and Nepal, but excluded Bangladesh.

At the core of managing international rivers is the fact that water flows (Alam, Dione and Jeffrey, 2009) and is incorrectly treated as a stock rather than a flow (Qaddumi, 2008). The basis of cooperation is the recognition that interdependencies, created by the transient nature of water, exist.

From an economic perspective, transboundary water problems can be thought of as unidirectional externality problems since transboundary river basins, by their very nature, create externalities due to the fact that the boundaries of the nations through which the water flows do not coincide with the boundaries of the river basins themselves. An externality arises when the production or consumption activities of one riparian have direct effects on the production or consumption of another riparian and implies a Pareto inefficient allocation of the resource (Dombrowsky, 2008). According to Rogers (2011) the unidirectional feature of water use means that the basin conflict resolution through mutual control of externalities that work reciprocally is generally ruled out. Aside from the water allocation problems that arise from sharing a common resource, there are other problems such as water quality degradation downstream as an effect of upstream use. Even when the negative effects are due to natural occurrences, they may be mistaken by downstream countries as man-made externalities and lead to further mistrust and tensions among riparians in the basin.

1.1.5 Benefit sharing

The use of benefit sharing has been suggested as a method of fostering cooperation in transboundary waters (Sadoff and Grey, 2002, 2005). In this context, benefit sharing is defined as the development of water use in its optimal location, and the distribution of the benefits derived from these uses, rather than the water itself, to users across the basin (Alam, Dione and Jeffrey, 2009). Hensengerth, Dombrowsky and Scheumann (2012) has a more general definition: "benefit-sharing can be seen as the translation into practice of international water law, and specifically the principles of equitable and reasonable utilization, and of the absence of harm, which the international and regional conventions emphasize."

One of the main arguments in focusing on the benefits derived from the use of water rather on the allocation of the water itself is that a zero-sum game of water sharing can be replaced by a positive sum game of benefit sharing (Dombrowsky, 2010). One way that this may occur is through the use of benefit sharing to bypass the issue of water and property rights. If the focus is shifted from the allocation of physical volumes of water to the various values derived from the use of water (including economic, social, political and environmental benefits), then riparians will view the problem as one of positive-sum outcomes associated with optimizing the benefits rather than the zero-sum outcomes associated with the division of water (Qaddumi, 2008). Qaddumi (2008) also argues that since cooperation in the management of transboundary water resources can be difficult, as a result of unclear and contested property rights, benefit sharing may also help to increase cooperation in international river basins. "The prospect of potentially gaining higher benefits by cooperating rather than by maintaining the status quo or by taking unilateral action encourages states to cooperate with each other in their use of shared rivers" (Hensengerth, Dombrowsky and Scheumann, 2012). Sadoff and Grey (2002) argue that by focusing on the benefits derived from the use of water in a river basin, rather than from the physical water itself, the perspective of basin planners may be broadened. They point out that in order to "negotiate the management and development of international shared rivers, riparians can focus their negotiations on the allocation of water rights or on the distribution of benefits derived from the use of water" (Sadoff and Grey, 2005). This insinuates that the sharing of rights (physical allocation) and the sharing of benefits are understood to be alternative negotiation strategies. Other authors question the separation between the negotiation of benefits and the negotiation of rights. Phillips et al. (2006) argued that the demand for the equitable allocation of water resources, and the approach of sharing benefits,

Table 1.1: Types of cooperation and benefits generated in international river basins (as proposed by Sadoff and Grey (2002))

Type of Benefit	Challenges	Opportunities
Increasing benefits to the river	Degraded water quality, watersheds, wetlands and biodiversity	Improved water quality, river flow characteristics, soil conservation, biodiversity and overall sustainability
Increasing benefits from the river	Increasing demands for water, suboptimal water resource management and development	Improved water management for agriculture/hydropower, flood-drought management, navigation, environmental conservation, water quality and recreation
Reducing costs because of the river	Tense regional relations and political economy impacts	Policy shifts from dispute/conflict to cooperation/development; from food/energy self-sufficiency to food/energy security; reduced conflict risk and military expenditure
Increasing benefits beyond the river	Regional fragmentation	Integration of regional infrastructure, markets and trade

are in fact two sides of the same coin and that an agreement on water allocations (rights) must happen prior to the sharing of benefits. van der Zaag, Seyam and Savenije (2002) argue that "the rights of the riparian countries sharing a common water resource have to be established before economic or financial transactions concerning water allocation can occur" and Richards and Singh (2001) conclude that "valuation of the use of water cannot be analytically separated from the allocation of property rights". Dombrowsky (2009) takes this debate a step further by pointing out that the sharing of rights and the sharing of benefits can be delinked depending on whether there are negative or positive externalities. In the case of negative unidirectional externality problems, a basic agreement on property rights (the right to abstract or pollute the water for example) is a prerequisite for any benefit-sharing scheme. "Once agreement on property rights has been reached, the parties may start trading these rights and optimizing the use of the resource" (Dombrowsky, 2010). In the case of positive unidirectional externalities (such as the provision of flood control benefits for the downstream party, by the upstream party, through water retention measures) no property rights to water are involved. The question, rather, is whether the downstream party that benefits from upstream measures has an incentive to contribute toward the provision of the positive externality (Dombrowsky, 2010). In this instance, the benefits gained through cooperation can be realized regardless of the allocation of water rights. There seems to be no consensus, then, in the debate between the sharing of water and the sharing of benefits in the literature.

The types of benefits that can be generated and shared are discussed by Sadoff and Grey (2002). They have classified the international river according to the type of benefits that can be derived: the ecological river ("benefits accorded *to the river*"), the economic river ("benefits to be reaped *from the river*"), the political river ("costs arising *because of the river*") and the catalytic river ("benefits enabled *beyond the river*"). Details of these classifications are given in Table 1.1.

Table 1.2: Forms of benefit sharing (as discussed by Klaphake and Scheumann (2006))

Benefit Sharing Mechanisms		Typical Applications
Compensation	Monetary	Financial transfers between riperians
		Participation in project costs, infrastructure financing or other measures (e.g. reduction of discharges)
		Payments for water usage to existing rights-holders
		Acquisitions of subsidiaries / joint ventures / direct investment
		Price and volume agreements for water and energy
	Non-Monetary	Allocation of water rights
		Agreement on allocation of quantities of energy
Issue Linkages	Within water sector	Realization of tradeoff deals with opposite cost-benefit allocation (e. g. improvement of navigability to sea against reduction of discharges on upper course)
		Concessions on water allocation in other river basins
	Outside of water sector	Trade concessions, transportation agreements, immigration issues, border controls, supply agreements (e.g. energy, oil), and the like

Phillips et al. (2006) describes the Inter-SEDE model (denoting the international finance components and the three categories of drivers: security, economic development, environment) which builds upon the classification by Sadoff and Grey (2002). Economic, environmental or security benefits can be generated and activities in these various spheres may have spill-over effects. They propose to identify security, economic and environment drivers in international river basins and, based on this, to then identify opportunities for development at various scales (household, sub-national, national, regional, global) within each of these spheres.

The benefit categories that have been developed by Sadoff and Grey (2002) and Phillips et al. (2006) are a starting point for benefit generation. They can also be used to aid in the understanding of the range of sectors that can be included in generating benefits from cooperation and of the possible size of the basket of benefits. However, neither Sadoff and Grey (2002) or Phillips et al. (2006) specifically address the question of how these benefits can be shared.

Klaphake and Scheumann (2006) identify and describe two methods of sharing benefits: compensation (side-payments) and issue-linkages. Descriptions of these mechanisms are shown in Table 1.2.

The World Commission on Dams (2000) presents definitions of benefit sharing mechanisms specifically with respect to large dam projects. These benefit sharing mechanisms, however, can be applied to other types of water infrastructure as well. These benefit sharing mechanisms are classified as monetary and non-monetary. Monetary benefit sharing mechanisms involve the sharing of part of the monetary flows generated by the operation of the infrastruc-

Table 1.3: Mechanisms of benefit sharing (as discussed in the World Commission on Dams (2000))

Benefit Sharing Classification	Mechanism	Notes
Monetary	Revenue sharing with local or regional authorities	revenue sharing through taxes on revenues or royalty regimes; may be the result of negotiations between local or regional authorities and the promoter or may be defined in the legislation
	Development funds	financed from power sales, water charges etc.; provide seed money for fostering economic development in the project-affected area
	Equity sharing or full ownership	allowing local or regional communities to partly or fully own a dam project; risk sharing as well as profit sharing with affected communities; communities may gain a degree of control over the design and operation of the project
	Taxes paid to regional or local authorities	taxing the infrastructure operators on the projectâĂŹs property value or other basis; State legislation defines the taxes to be paid to the local/ regional authorities, based on a percentage of project sales or net income
	Preferential electricity rates or other water-related fees	a form of revenue sharing; results in less revenue for the dam owner and avoided costs for beneficiaries
Non-monetary	Livelihood restoration and enhancement	securing income through employment in the construction and in the operation of the project; possible employment in the agricultural, fishery or recreational sectors
	Community development	through increasing the access and quality of primary services, such as domestic water supply and electrification, transportation, health and education; facilitate access to markets and common resources (e.g. forests)
	Catchment development	custodianship of catchment resources; opportunities to improve the management and benefit generation of the catchment area, for example through improved irrigation, reforestation etc.

ture with the affected communities to compensate project-affected populations for lost assets and lost access to resources. Non-monetary benefit sharing schemes reflect the development strategy element of a comprehensive compensation policy aimed at restoring and improving the livelihoods of project-affected populations. Table 1.3 lists these mechanisms.

In a subsequent paper, Sadoff and Grey (2005) suggest alternative mechanisms of benefit sharing, including direct payment for water use (e.g., municipal or irrigation supplies), direct payment for benefits (e.g., fisheries, watershed management) or compensation for costs (e.g., inundated land, pollution), purchase agreements (e.g., power, agriculture products), financing and ownership arrangements (e.g., power infrastructure) and broadened bundle of benefits, including provision of unrelated goods and services and less tangible (e.g. reputation) benefits.

The discussed benefit sharing mechanisms have been adopted in a wide variety of agreements between riparian countries. Klaphake and Scheumann (2006) detail 18 different benefit sharing agreements, mostly centred on dam construction designed to generate and use hydropower. The Lesotho Highlands Project on the Senqu/Orange river basin applies mechanisms such as direct payments for water, purchase agreements and financing arrangements. The agreement between India and Nepal on the Mahakali River is based on cost sharing and a power purchase arrangement. The India-Bhutan agreement on the Chukha hydropower project includes payments made by India to Bhutan for power exports. Other examples of benefit sharing in international river basins are detailed by Yu (2008), Phillips et al. (2006), Hensengerth, Dombrowsky and Scheumann (2012) and Daoudy (2007).

There is a rapidly growing body of literature which mainly discusses benefit sharing from a conceptual point of view. This literature introduces and defines different approaches, stopping short of providing practical institutional arrangements for the sharing of benefits. For example, Qaddumi (2008) provides a starting point for the operationalization of transboundary benefit sharing. Drawing on experience from a number of river basins, the author discusses several practical mechanisms that might foster movement towards cooperation, including the quantification of benefits and costs of optimal water management, taking care to address equity concerns, and recognizing the link between volumetric water allocations and benefit sharing. The main highlights of this study are that the recognition of the link between national water policies and transboundary water issues is essential, the involvement of stakeholders is required in order achieve viable solutions, and monitoring and evaluation is vital as a learning tool and consensus builder. Finally, the author suggests that attention needs to focus on areas such as the mechanics of institution building and the creative application of existing economic tools to assess potential "win-win" scenarios. Skinner, Naisse and Haas (2009) analyze experience and approaches in sharing benefits from large dams and makes proposals for moving forward on this issue in West Africa. They suggest that the best approach is through multi-stakeholder partnerships/dialogue (government, industry and civil society) that will help to define a viable approach that has both a practical and ethical orientation, that adds value for all stakeholders, that creates synergy with existing government development policy initiatives and that builds on and reinforces the roles of existing institutions, local development and water resource management institutions. Suhardiman et al. (2014) examine how the notion of benefit sharing is articulated and applied in the debate surrounding the merits of existing and future hydropower development in the Mekong region. The conceptual strengths and weaknesses of benefit sharing are discussed, within the broader context of land and water resources and environmental governance, and they argue that while benefit sharing provides an entry point for placing the debate on hydropower development within the perspective of social justice, better understanding of governance structures and processes is needed. Their primary message is that innovations in policies and programs need to be analyzed in the context of wider governance structure, processes, and outcomes. These authors agree that the best approach for benefit sharing in transboundary river basins lies in the development of institutional arrangements, which combine the policies, systems, and processes that an organization can use to efficiently legislate and manage its activities in order to fulfill its mandate. There is also an emphasis on stakeholder involvement in order to ensure the acceptance and feasibility of the solutions.

Institutional arrangements for benefit sharing can be categorized into 3 components: water law, water policy, and water administration (Bandaragoda, 2000). Existing water laws should be supported (such as the UNWC in the case of transboundary river basins), water policy is needed to define the rules of water allocation, benefit allocation and stakeholder involvement, and water administration is required to define organizational procedures, accountability mechanisms and information storage and collection procedures. This approach would require the development of new institutions or the restructuring of existing ones to include the mandate of benefit sharing. However, in the current literature, it is still unclear how these institutions would look. Models of possible arrangements need to be built and the functioning of these arrangements need to be explored. Quantitative methods provide tools which can be used to investigate these types of arrangements, and to help describe and understand how they work.

1.2 Modelling water and benefit sharing in transboundary river basins

1.2.1 Modelling water sharing

Hydro-economic models

Hydro-economic models have traditionally been used in the study of water sharing in transboundary river basins. These models generally represent all major spatially distributed hydrologic and engineering parts of the river system (Harou et al., 2009) including water balance components (such as river flows, evaporation, natural groundwater recharge, etc.) and water supply infrastructure and operations (such as canals, reservoirs, hydropower generating stations, wastewater treatment plants, etc.). These hydrologic and engineering features are included in a node-link network representing the system. This node-link characteristic of hydro-economic models is particularly useful when analyzing water use and demand relationships across economic sectors (Cai, McKinney and Rosegrant, 2003; Ringler, von Braun and Rosegrant, 2004; Rosegrant et al., 2000). In contrast to engineering models that minimize costs or maximize particular outputs (for example, water availability for irrigated crops), hydro-economic models determine how units of water should be allocated across time, space, and uses to produce the greatest overall economic net benefit (Harou et al., 2009) through the assessment of demand curves for water users and the maximization of the total consumer surplus.

Different designs and options exist in hydro-economic models including simulation and optimization models.

Simulation models can handle large amounts of details and nonlinearities, and are well suited to evaluating 'what if' scenarios related to specific types of changes that can affect the economics of water resource systems. They are often used to assess changes in water demand as a result of changes to input such as population growth, irrigation expansion or changes in demand management. They can also be used to evaluate technology and infrastructure improvements (de Fraiture et al., 2001; Rosegrant and the IMPACT Development Team, 2012). One important shortcoming of simulation hydro-economic models, however, is the large number of scenarios that can arise in multi-dimensional systems under consideration. This is, however, somewhat balanced by the lower computational requirement when compared to optimization models, which can result in a more rapid solution to the model and also allows for expanded possibilities for considering smaller time steps and longer time horizons (Bekchanov, Sood and Jeuland, 2015).

Optimization hydro-economic models are also widely used for river basin management studies. These models include an objective function that is either maximized or minimized subject to a variety of economic and biophysical (mass balance or other) constraints. The form of the objective function varies depending on the problem to be solved. Some models seek to maximize the economic benefits of a particular set of water uses (Ringler, von Braun and Rosegrant, 2004), while others look to minimize costs subject to some expected level of output or other criteria (Jenkins et al., 2004).

Optimization hydro-economic models typically assume centralized management and have an important limitation in that they generally assume perfect foresight for future hydrology and, as a result, may overstate benefits. Regardless, these models do provide a starting point for the comparison of different water allocation alternatives (Bekchanov, Sood and Jeuland, 2015; Jalilov, Varis and Keskinen, 2015; Jalilov et al., 2016), for the determination of the optimal operation of new and existing infrastructure (Goor et al., 2010; Goor, Kelman and Tilmant, 2011; Arjoon et al., 2014), and for the assessments of the benefits of water cooperation or coordination, including the cost of non-cooperation (Teasley and McKinney, 2011; Jeuland et al., 2014; Tilmant and Kinzelbach, 2012; Whittington, Wu and Sadoff, 2005; Ringler, von Braun and Rosegrant, 2004). As well, optimization models are particularly relevant in economic theory, as the shadow price, or marginal value of water, at each node in the system is available. These prices represent the true value of water and can be used to guide water pricing (Pulido-Velazquez, Alvarez-Mendiola and Andreu, 2013), to determine the economic value of different water use sectors (Tilmant et al., 2012), in water accounting (Tilmant, Marques and Mohamed, 2014) and in the sharing of economic benefits (Arjoon, Tilmant and Herrmann, 2016).

Comprehensive overviews of hydro-economic models and their uses have been carried out by Harou et al. (2009), Cai (2008), Brouwer and Hofkes (2008) and Bekchanov, Sood and Jeuland (2015).

The centralized approach carries a strong institutional assumption and presupposes central planning or perfectly functioning water markets (Britz, Ferris and Kuhn, 2013) which are seldom found in reality. This issue is the main driver behind the development of agent-based modelling.

Agent-based models

Agent behaviour has been represented in decentralized optimization-based frameworks to move away from the assumptions full cooperation and central planning. An "agent" in the context of water allocation may refer to water users, institutional actors, etc. An example of a multi-agent watershed management system is developed in Yang, Cai and Stipanović (2009). The approach considers that all water users are individual agents that make decisions through interactions with each other, with a coordinator acting to resolve conflicts by balancing the decisions of different agents. This system is applied to the allocation of water in the Yellow River basin (Yang, Zhao and Cai, 2012) and used to compare administrative and market-based water allocation (Zhao, Cai and Wang, 2013). In another application of agent-based optimization Giuliani and Castelletti (2013) analyze various levels of information sharing and cooperation between agents. In general, this approach aims to represent the more realistic behaviour of agents in a river basin (Berger et al., 2007; Bonabeau, 2002).

Game theory

One of the deficiencies of optimization techniques is that they assume every stakeholder is acting voluntarily to achieve optimal system-wide performance. However, the optimal system-wide outcome does not necessarily mean the best outcome for every individual stakeholder. It is important to provide motivation to every stakeholder, such as obtaining greater (or, at least, not any less) economic benefits, in order to achieve the best system performance.

With this in mind, game theory, the mathematical study of conflict and cooperation, has been suggested as an alternative to optimization techniques for water allocation in transboundary river basins to provide a framework for the study of the strategic actions of individual decision makers to develop more widely accepted solutions (Madani, 2010). The stable outcomes of games are not necessarily Pareto-optimal. Players are concerned with maximizing their own benefits and this attitude often results in non-cooperative behaviours even when cooperative behaviour may be more beneficial to the parties involved. As a result, game theory may provide a more realistic simulation of the interest-based behaviour of the stakeholders (Madani, 2010).

Games can be cooperative or non-cooperative. Cooperative game theory deals with those games in which groups or coalitions of players make decisions together and normally aim to fairly and efficiently share the incremental benefits of cooperation between the players. In the context of transboundary river management, cooperative game theory concepts can be used to develop functional water allocation schemes. Example transboundary river conflicts analyzed by cooperative game theory include the Ganges river conflict between Bangladesh and India (Kilgour and Dinar, 2001), the Euphrates and Tigris rivers conflict between Iraq, Syria, and Turkey (Kucukmehmetoglu and Guldmann, 2004), and the Syr Darya river basin conflict between Kyrgyzstan, Uzbekistan, and Kazakhstan (Teasley and McKinney, 2011). Wang, Fang and Hipel (2003), Wang, Fang and Hipel (2008) and Xiao, Hipel and Fang (2016) also apply cooperative game theory in the development and analysis of a comprehensive water allocation framework. While cooperative game theory is promising, its application is limited to problems in which utility information is available for all parties and the incremental benefits of cooperation can be determined.

Non-cooperative game theory deals with games in which players compete and make decisions independently, which is useful in studying the strategic behaviours of riparian parties and the feasibility of cooperative solutions, and in providing strategic insights into conflicts (Madani and Hipel, 2011).

Example transboundary river conflicts analyzed by non-cooperative game theory concepts include the Jordan river conflict between Jordan, Israel, Lebanon, Palestine, and Syria (Madani and Hipel, 2007) and the Nile river conflict between Burundi, Congo, Egypt, Eritrea, Ethiopia, Kenya, Rwanda, Sudan, Tanzania, and Uganda (Elimam et al., 2008). These methods normally rely on qualitative information to find the likely outcomes of conflicts based on various stability definitions, which incorporate a range of decision makers' (players) characteristics such as risk attitude, foresight level, and information quality (Madani and Hipel, 2011; Madani, 2013). While these methods provide valuable insights into strategic conflicts and can help find possible resolutions to the conflict, their results are not necessarily quantitative and in most cases are only appropriate for studying as games with discrete solutions (strategies or actions).

Some researchers believe that non-cooperative game theory solutions may lead to the over-exploitation of shared water resources and that these are typically inefficient (Ambec and Ehlers, 2008). Others have argued that there is some justification for players to prefer non-cooperation (Ariel and Nigatu, 2013), for instance, in the case of high coordination costs that are associated with the cooperation of a large numbers of agents or historical and cultural disputes among riparian states (Mianabadi et al., 2015).

Bankruptcy methods

Recently, some researchers have examined bankruptcy rules as a method to solve water resources allocation problems. In a bankruptcy situation, the amount of an available resource (or estate) is insufficient to cover the total claims of creditors to the resource. The aim of bankruptcy rules, then, is to fairly divide the scarce resource among the creditors. Due to the impossibility of defining a unique notion of fairness, different bankruptcy rules have been proposed. Thomson (2003) and Thomson (2013) present a comprehensive overview of a large number of bankruptcy rules and the properties that define fairness for each of these.

There are a few reasons for using bankruptcy rules to address water allocation problems in transboundary river basins. They have relatively simple mathematical structures and can be easily used by policy makers to solve water allocation problems (Ansink and Weikard, 2012). As well, bankruptcy theory, which is a form of cooperative game theory, provides solutions that are more useful than conventional cooperative game theory solutions when the information about the utilities of stakeholders cannot be calculated or may not be accepted by all parties (Zarezadeh, Madani and Morid, 2012; Madani and Zarezadeh, 2012).

The applicability of bankruptcy rules to water allocation problems in river basins has been investigated by Ansink and Weikard (2012) who proposed a new bankruptcy allocation rule to take into account the fact that agents are ordered linearly in a river basin. Zarezadeh, Madani and Morid (2012) applied four common bankruptcy rules (PRO, AP, CEL and CEA) to suggest fair allocation plans under different climate and development scenarios in the Qezelozan-Sefidrood River basin in Iran. Madani, Zarezadeh and Morid (2014) tested various bankruptcy optimization models, based on four bankruptcy rules, for the allocation of water in a river basin with respect to the time sensitivity of water deliveries during the planning horizon. Sechi and Zucca (2015) introduced a new cooperative bankruptcy game to allocate water resources in a system in Sardinai, Italy. Mianabadi et al. (2014) developed a new bankruptcy rule to allocate water according to the UN watercourse convention and developed a weighted bankruptcy rule to investigate the water allocation problem in the Tigris River basin (Mianabadi et al., 2015). Oftadeh, Shourian and Saghafian (2016) applied two bankruptcy rules to analyze a conflict between irrigation water demand in three provinces in the Zarrinehroud River basin and downstream Lake Urmia. In addition, a comprehensive review of the link between river sharing problems and bankruptcy theory is presented by Beard (2011).

1.2.2 Modelling benefit sharing

Benefit sharing in river basins has traditionally been studied and analyzed from the point of view of hydropower infrastructure planning. These cases often look at the sharing of anticipated and actual revenue, that can be earned by a hydropower plant operator, from the production and sale of electricity, with residents of hydropower watersheds. These benefits help offset the impacts of dam construction and operation. For example Lebel et al. (2014) look at defining the benefits from a hydropower watershed (specifically the Sirikit Dam hydropower watershed in Northern Thailand) and how these can be shared, using different benefit sharing models. McCartney (2009) discusses the use of decision support systems to optimize benefits from large dam operation and Brown et al. (2009) propose a tool for evaluating the relative costs and benefits of dam construction based on multi-objective planning techniques.

Recently, benefit sharing studies, although limited, have started to focus on the sharing of the benefits of water use itself. These attempt to study cooperation with respect to water use rather than infrastructure planning. Most efforts, thus far, have concentrated on developing a methodology for sharing economic benefits by focussing first on optimizing the benefits of water use, then on reallocating the additional net benefits obtained to ensure equity. For example, in Kahil, Dinar and Albiac (2016), additional benefits obtained through the application of a cooperative water sharing agreement are allocated using cooperative game theory concepts. Mehrparvar, Ahmadi and Safavi (2016) also uses game theoretic approaches, including the Shapley, Nucleolus and Nash-Harsanyi methods to determine payoffs to each player in the benefit reallocation process. Wang, Fang and Hipel (2008) apply cooperative game theory, as well, to investigate how the net benefits of cooperative water allocation can be fairly reallocated to achieve optimal economic reallocation of water resources. In these studies, a necessary condition for cooperation in the basin is that the benefits obtained by each cooperating water user, under full cooperation (grand coalition), are greater than what each player can obtain under non-cooperation (singleton coalition), or by participating in partial cooperative arrangements (partial coalitions). The sharing of benefits are ultimately determined through stability analysis procedures in which indicators are used to quantify the dissatisfaction level of a user within the sharing system. This insinuates that water users do not have a say in what is considered equitable. However, it has been argued that the notion of equity, or fairness, actually involves a cultural component that should be incorporated into any type of water policy and, therefore, stakeholder involvement in decision-making is a significant determinant in the judgement of fairness (Syme, Nancarrow and McCreddin, 1999; Asmamaw, 2015). This has been discussed previously in Section 1.1.5.

Ding et al. (2016) developed a parallel evolutionary search algorithm to introduce a mechanism to redistribute the central planner revenue value among the competing agents, based on their contribution to the central solution, and applied this to the Nile River. In a centralized solution, the aggregated benefits of all water users were used to determine the optimal system revenue. Then, in a decentralized solution, a parallel evolutionary approach was developed to find the contribution of each user to the whole system. In a parallel evolutionary approach, the optimization problem of individual agents, or groups of agents, are solved in parallel, while interacting with each other. In this study, one agent at a time is removed from the grand coalition and the utility maximization of the agent is solved in parallel with the aggregated utility maximization of the remaining group to determine the contribution of each user to the coalition. In this way, revenues were reallocated, proportional to the contribution calculation for each user, thereby guaranteeing a fair and efficient allocation of water to all users. The authors suggest that, compared to the central solution, these results take into account the self-interest of individuals, by providing a fairer distribution to those with greater accessibility to the resource. Other authors, however, argue that, often, cooperation between water users is in their self-interest and, in situations in which it is not in the immediate interest of all parties involved, international customary law may inform the parties on how to settle disputed property rights in an equitable manner in order to realize the gains of cooperation (Dombrowsky, 2007).

In the studies presented above, there is a general agreement that the maximization of economic benefits, through cooperative water allocation, is a prerequisite to benefit sharing. Achieving trade-offs between efficiency and equity can occur when these two principles are coupled to first maximize the benefits available and then share these in an equitable manner. The application of efficiency in these studies, is, however, considered to be less of a defining principle of water allocation and more as an important, but ancillary tool to the equitable sharing of benefits, which is an idea that has been supported in the literature (Roa-Garcia, 2014).

Where these studies differ is in their presentation of how to share the benefits of cooperation. In all cases, sharing rules that have their own definition of equity are applied. None have focussed on what stakeholders believe is fair.

1.3 Summary

Overall, this literature review highlights the importance of efficiency and equity in the sharing of water and benefits in transboundary river basins to deal with the question of water scarcity. The water management sector generally agrees that cooperation is essential to meet these two objectives. Cooperation is required for the efficient sharing of water and recent studies favour the consideration of efficiency as a prerequisite for equitability. There is a general consensus that the coupling of efficiency and equity requires that institutional arrangements be designed that include policies and processes for water allocation and benefit sharing. As well, fairness needs to be defined on the stakeholder level to ensure the adoption and utility of the solutions. However, investigations of possible arrangements are lacking in the current literature. With this in mind, an institutional arrangement was developed, as part of this PhD project, which is described in detail in the next chapter.

Chapter 2

Methodology

In order to carry out the activities required to answer the research questions upon which this PhD project is based, a market-based institutional arrangement was designed in which economically efficient water allocation is coupled with equitable benefit sharing. This type of arrangement may provide an alternative to the types of agreements on international river basins which attempt to define the rights of users to water. These agreements are often perceived as zero-sum games and can lead to distrust and tension between riparian countries, as is the case in the Eastern Nile River Basin. What is presented, instead, is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements that are based on water rights alone. For example, with respect to the Nile Basin, the current agreement which drives water allocation legally constrains Sudan to 18.5 km^3 of water use, annually. Sudan, however, has available land resources to expand irrigation and use much more water than this (Allan et al., 2013), but is limited due to the agreement. Also, uncertainty with respect to changing climate and the possibility of increased evaporation, uncertain hydrology and sea level rise could create an imbalance in water demand and supply in the basin. For instance, a rise in sea level would result in the loss of agricultural land in the Nile Delta, and, subsequently, a large portion of Egypt's historic water use may no longer be required (Whittington, Waterbury and Jeuland, 2014).

It should be noted that this institutional arrangement presents a hypothetical scenario. However, technological changes (for example, increased availability of massive remote sensing data) combined with the need to achieve greater efficiency due to external pressures, such as population growth and climate change, might trigger major regulatory reforms in the water sector. This was seen in the energy sector in the late XXth century when, before 1970, energy generation was widely believed to be part of a natural monopoly. Technological developments such as cheap gas-fired power plants, combined with costly and inefficient investments made by the local monopolies, suggested that competition was needed and led to the introduction of deregulated electricity markets. So, the methodology must be seen as a prospective analysis, concerned with a future situation that does not currently exist and with how the institutional arrangement would perform under these conditions.

In this chapter, after a description of this arrangement is provided, the modelling tool used to determine water allocation in the case study basin, and the rule used to share the benefits of water use, are detailed.

2.1 Institutional arrangement

The general methodology, presented in **Paper II** depends on the existence of a river basin authority (RBA) to play the role of market operator in an auction-based market system. The assumption of an existing RBA is not unrealistic given that there are a number of river basins that already have this type of organization in place (OMVS on the Senegal, MRC on the Mekong, ZAMCOM on the Zambezi, NBA on the Niger River, etc.) and others that are working toward this goal (Volta Basin Authority, for example).

The RBA, based on water demand information, identifies economically efficient allocation policies which are then imposed on the water users, who are charged for the resource. These payments are collected and then redistributed to ensure equitability among the users. In this particular arrangement, the mandate of the RBA consists of (1) collecting information on water use and productivity, (2) efficiently allocating water between the different agents in the system, based on the information collected in the first step, (3) preserving the hydrologic integrity of the river basin, and (4) coordinating the collection and redistribution of the benefits associated with the optimal allocation policies.

This benevolent water manager is a non-profit, regulated organization that acts as a third party operator of the water resources system. In other words, productive use and allocation decisions are separated: the RBA does not directly put water to productive use for its own benefit. Instead, it coordinates allocation decisions throughout the system based on the offers provided by eligible water users, and tries to achieve allocative efficiency by ensuring that water is consumed by those who value it most highly.

As part of the application of this methodology, historical water use rights are disregarded. The RBA may be considered as the owner of bulk (raw) water in the basin. Since the RBA is a supranational institution, this means that the riparian countries actually own the water. However, once the allocated water is diverted to the user, the water belongs to the user (who has paid for it).

The four parts of the arrangement are shown in Figure 2.1 and presented, in detail, below.

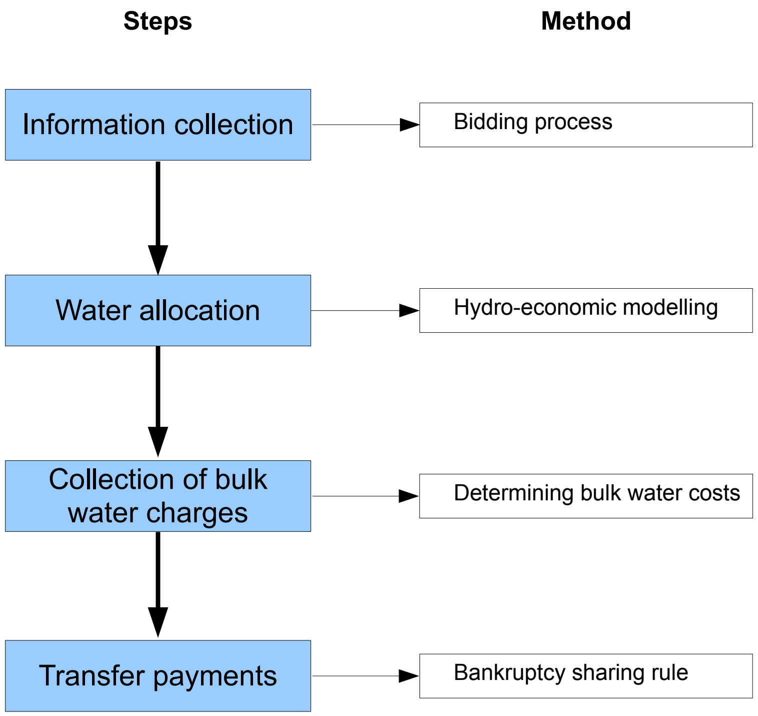


Figure 2.1: Institutional arrangement and methods used at each step.

2.1.1 Information collection

In the first step, the RBA collects information that is required to assess the demand curves, or at least the productivity (unit net benefit), of all users in the system, once at the beginning of a time period. The information is validated to ensure that it is complete and reasonable since the economically efficient allocation of water, in the next step, is based on this. Information collection is based on a bidding process in which agents offer to buy water at a given price. All water users are granted equal access to the resource.

There may be an incentive for water users to cheat when supplying data in this type of arrangement (for example, by making false bids that would benefit them through higher water allocations). These incentives will remain even if the RBA is able to audit the bids. For industrial uses, including hydropower generation, cheating might be more difficult because the market prices and production functions are often well characterized. The main challenge is in the agricultural sector because (a) it is often the largest water use in the basin and cheating might have serious basin-wide consequences, and (b) the heterogeneity, in terms of cropping patterns and irrigation efficiencies, requires that significant data be collected and analyzed to audit the demands. However, due to river basin closure, there are strong incentives to strengthen the monitoring of river basins, either directly (on-site measurement stations) or indirectly (remote sensing). Various initiatives, at different levels, demonstrate that significant effort and financial resources are being devoted to observations of water resources. For example, the Surface Water and Ocean Topography (SWOT) satellite mission (anticipated launch date 2020) and the Sentinel-3 satellite mission. The incentives to cheat might not be eliminated but they can be suppressed, or at least kept within limits, through a robust monitoring system and a strong RBA to negotiate disputes. An example of how this has worked, with good success, is the Indus River basin. Zawahri (2009), in discussing the Permanent Indus Commission, states that the commission's ability to monitor development of the river system has allowed it to ease the fear of cheating among member states and to confirm the accuracy of all exchanged data.

2.1.2 Water allocation

Once water user information has been collected, allocation decisions are identified by matching demand with supply in a cost-efficient way, i.e., by giving priority of access to users with the highest productivity. In the Eastern Nile River Basin case study, a hydro-economic model is employed to determine the allocation of water between users at the same site and over the basin (comprising a number of sites). The marginal value of water and economic benefits at each site is also available from the model. Details on the hydro-economic model used in the case study are found in Section 2.2.1.

2.1.3 Collection of bulk water charges

Based on the water allocation decisions, transactions occur between the RBA and the water users and the users must pay the RBA for the water allocated to them. The RBA charges for the water in order to cover the operating costs associated with its mandates (conservation, coordination, compensation). Payment for the use of bulk water has recently been addressed by the United Nations in their 2014 World Water Development Report (United Nations World Water Assessment Programme, 2014). They state that economic instruments, such as markets for buying and selling a resource (such as water) or the imposition of water use tariffs, could create incentives for more efficient use. And, in fact, payment for bulk water supply has been established in recent water laws in Zimbabwe, Tanzania and Mozambique (World Bank, 2008).

The cost of water, to a user, is the marginal water value, or shadow price (λ), at the site of water abstraction or use, which is calculated by the hydro-economic model. Economic theory indicates that for efficient water allocation to occur, the price that a user pays for the resource must be equal to the marginal value of still available opportunities of water use, which reflects the social cost of using water at a particular site. If the user pays less than this, the resource is over-consumed or over-utilized, as no efficient rationing occurs. Conversely, a user price higher than the marginal value would result in underconsumption/underutilization. In the case of consumptive users, such as irrigation agents, water is purchased from the RBA at the marginal water value at the site of abstraction. Non-consumptive users, such as run-of-river hydropower plants, buy inflow from the RBA at a price equal to the difference between the

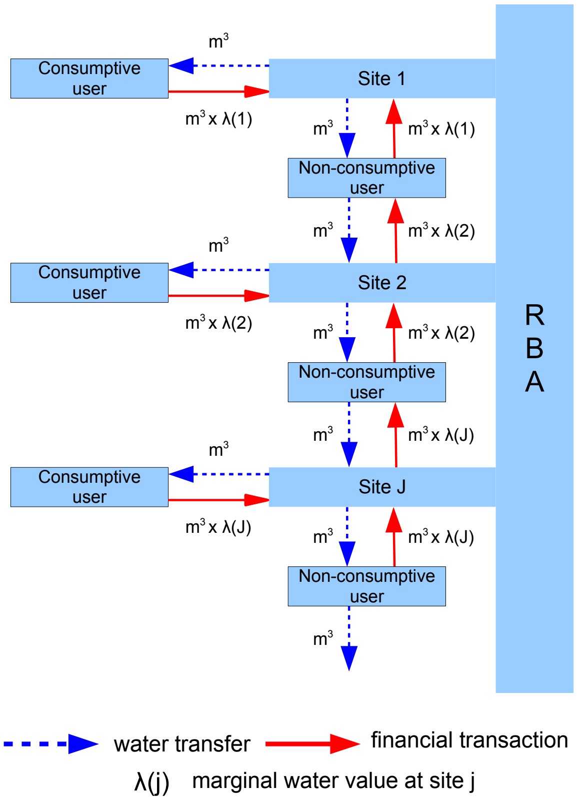


Figure 2.2: Collection of bulk water charges.

marginal value of water at the user site and the marginal value of water at the downstream site (Figure 2.2).

At this point in the methodology, the RBA has collected an amount of money, referred to as the estate (E), that can be shared among the water use agents, as described below.

2.1.4 Transfer payments

Using an axiomatic approach, a method of sharing the estate is determined. The aim of the axiomatic approach is to find and capture the notion of fairness that water users agree upon. The approach then sets out axioms (properties) that fairness should or should not satisfy. Finally, these properties are translated into a sharing rule that quantifies the particular definition of fairness. How the benefits are shared depends entirely on this definition, as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing, may be required. Since each river basin will have a different definition of fairness (depending on conditions in the basin and the outcome of negotiations with the water users), each river basin will likely have its own unique sharing rule.

This approach depends on allowing all stakeholders a place at the table, which is challenging, especially for large systems with diversified water use activities. In the irrigation sector, farmers could send a representative, e.g. a member of a water user association. For uses of water as a public good (e.g. environmental flows), the representative could be the Ministry of Environment of the country of interest. For municipal uses, the system could be designed in such a way that a minimum amount of allocated water is guaranteed (a fixed constraint in the allocation system) while quantities beyond that minimum would be part of the pool for which municipalities would have to bid. Industrial and power companies are easier to handle. Another possibility is that the government (or at least a high level representative of the stakeholders) has the ultimate negotiation power, akin to negotiations on trade liberalizations. Clearly, different lobbies exist that would try to influence the government, implying, ultimately, some form of compensation (the analysis of which lies outside the scope of this thesis). All users that can be rationed (mainly private water users) are allowed a place at the table for the purpose of defining fairness with respect to transfer payments.

In the case study, bankruptcy methods have been applied in the determination of transfer payments. Details on the development of the sharing rule are found in Section 2.2.2.

2.1.5 Institutional arrangement and the UNWC

Along with addressing a number of challenges with respect to the success of cooperative development in transboundary river basins, including the quantification of cooperative benefits, the determination of the necessary conditions needed to manage these benefits, the negotiation of benefit allocation based on equity, and the involvement of stakeholders, the described methodology is also in line with global initiatives for the management of international river basins. It upholds two of the fundamental principles of the UNWC: the equitable and reasonable utilization of water, which stipulates that states should reconcile any competing claims to a watercourse on the basis of equity (Articles 5 and 6); and the general obligation to cooperate (Article 8). As well, because a basin-wide authority must exist to oversee the institutional arrangement, the possibility of addressing other principles of the UNWC exists, such as: the principle of notification and consultation, whereby states must notify, exchange information and, if necessary, consult and negotiate with other riparian states on the possible effects of planned measures that may have significant adverse effects on other riparian states (Part III); the regular exchange of data and information, which obliges the watercourse states to exchange data and information with respect to the condition of the watercourse (Article 9); and the peaceful settlement of disputes, which requires states to settle their disputes in a peaceful manner via a range of mechanisms such as negotiation, mediation, conciliation etc. (Article 33). In each of these cases, the fact that an RBA is in charge of collecting information with respect to managing the benefit sharing methodology strengthens the possibility of this organization being a central depository for other data and information in the basin. As well, conflict resolution mechanisms are an important part of the mandate of many RBAs including the Permanent Indus Commission in the Indus River basin, the OMVS on the Senegal River, the Permanent Okavango River Basin Water Commission (OKACOM) and the Niger Basin Authority (NBA). Finally, the inclusion of water quality and ecosystem services, such as environmental flows, as a water use or constraint in the hydro-economic model will also enable the methodology to approach the principles of obligation not to cause significant harm (Article 7) and the protection of ecosystems, whereby states are under an obligation to protect and preserve the ecosystems of an international watercourse (Article 20).

The institutional arrangement, described in this section, relies on a modeling tool to produce economically efficient allocation policies and on a sharing rule to ensure equity among the users. The hydro-economic model and bankruptcy method used to perform these tasks, in the application of the arrangement to the Eastern Nile River Basin, are described below.

2.2 Modelling tools

2.2.1 Hydro-economic modelling: Determining efficient water allocation policies

A stochastic hydro-economic optimization model was employed to analyze inter-sectoral water allocation in a transboundary river basin in **Activity #1** and to determine the economically efficient allocation policies that would maximize basin-wide benefits in **Activity #2**.

The model is formulated to maximize the expected economic returns associated with the allocation decisions over a given planning period, taking into account the main hydraulic infrastructure and water demands. Denoting t as the index of time (stage), T as the end of the planning period, b_t as the one-stage benefit function at stage t, u as the vector of allocation (decision) variables, w as the vector of state variables, q as the vector of stochastic inflows, α as the discount factor, v as the terminal value function, f as the transition from state t to stage $t+1$, g as the set of functions constraining the decisions, and h as the set of functions constraining the state, the optimization problem can be written as:

$$Z^* = \max_{u_t} \left\{ \underset{q_t}{\mathbb{E}} \left[\sum_{t}^{T} \alpha_t b_t(w_t, u_t) + \alpha_{T+1} v(w_{T+1}) \right] \right\} \tag{2.1}$$

Subject to

$$g_{t+1}(u_{t+1}) \leq 0 \tag{2.2}$$

$$h_{t+1}(w_{t+1}) \leq 0 \tag{2.3}$$

$$w_{t+1} = f_t(w_t, u_t, q_t) \tag{2.4}$$

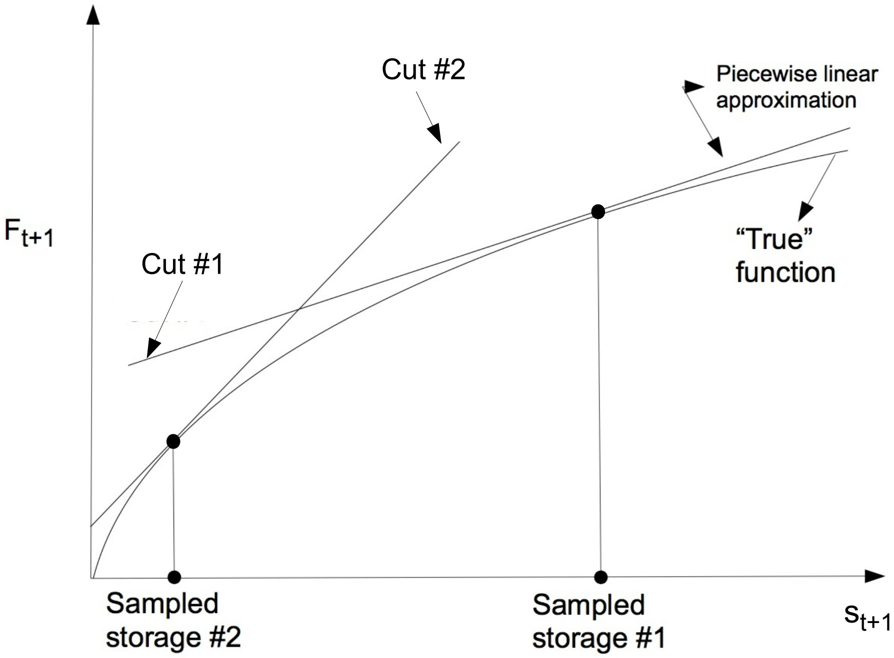


Figure 2.3: Piecewise linear approximation of the benefit to go function F_{t+1}.

where $\mathbb{E}$ is the expectation operator and Z^* is the basin-wide net benefit associated with the optimal allocations $(u_1^*, u_2^*, ..., u_T^*)$.

The optimization problem (2.1)-(2.4) is solved using the stochastic dual dynamic programming (SDDP) algorithm. As the name indicates, SDDP is an extension of stochastic dynamic programming (SDP) that removes, to a large extent, the computational limitations of SDP (the "curse of dimensionality") by constructing an approximation of the problem. Details of SDP and SDDP are presented in Appendix C.

The one-stage SDDP optimization model for a water resource system whose dominant uses are hydropower generation and irrigated agriculture can be written as:

$$F_t(s_t, q_{t-1}, y_t) = \max_{u_t} \{b_t(s_t, q_t, s_{t+1}, r_t, y_t) + \alpha_{t+1} F_{t+1}\} \tag{2.5}$$

where s is the vector of storage, q is the vector of natural inflows, y is the volume of water diverted to the irrigation schemes from the beginning of the irrigation season to the current stage t, r is the vector of reservoir releases and F is the benefit-to-go function (the benefits between time t+1 and T, or the future benefits). In SDDP, F_{t+1} is approximated using the piecewise linear function (Figure 2.3). The maximization occurs to the extent permitted by the following constraints:

The mass balance constraint:

$$\mathbf{s}_{t+1} - C^R(r_t + l_t) - C^I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t \tag{2.6}$$

where C^R and C^I are the connectivity matrices representing the topology of the system and the irrigation return flows, respectively, l is the vector of spillage losses, e is the vector of evaporation losses, and i represents irrigation water withdrawals. Lower and upper bounds of this constraint are defined as:

$$\underline{s}_{t+1} \leq s_{t+1} \leq \overline{s}_{t+1} \tag{2.7}$$

which ensures that water levels in the reservoir do not exceed the maximum capacity ($\overline{\mathbf{s}}_{t+1}$) or the dead storage capacity ($\underline{\mathbf{s}}_{t+1}$).

The limits on reservoir releases:

$$\underline{r_t} \leq r_t \leq \overline{r_t} \tag{2.8}$$

which are introduced to ensure maximum turbining capacity of the hydropower station and to maintain minimum downstream flow for water quality, navigation etc.

The hyperplanes used to approximate the benefit-to-go function F_t:

$$\begin{cases} F_{t+1} - \boldsymbol{\varphi}^1_{t+1} s_{t+1} - \boldsymbol{\eta}^1_{t+1} y_{t+1} \leq \boldsymbol{\gamma}^1_{t+1} q_t + \boldsymbol{\beta}^1_{t+1} \\ \vdots \\ F_{t+1} - \boldsymbol{\varphi}^L_{t+1} s_{t+1} - \boldsymbol{\eta}^L_{t+1} y_{t+1} \leq \boldsymbol{\gamma}^L_{t+1} q_t + \boldsymbol{\beta}^L_{t+1} \end{cases} \tag{2.9}$$

where φ, γ, η and β are hyperplane parameters and L is the number of cuts. Details on how these parameters are derived can be found in Goor et al. (2010).

The immediate benefit function $b_t(.)$ is defined by the sum of the net benefits from energy and irrigation minus penalties for not meeting operational constraints:

$$b_t(.) = HP_t + IR_t - \xi_t^{'} z_t \tag{2.10}$$

where *HP* is the benefits from hydropower, *IR* is the benefits from irrigation, and z is a vector of slack variables with the violations of operational constraints (energy deficit, environmental flows, etc.) which are penalized in the objective function by the vector of penalties ξ ($/unit of deficit or surplus)

The first term on the right hand side of Equation(2.10) is the immediate short-run net benefits from hydropower generation :

$$HP_t = \tau_t \sum_{j=1}^{J} (\pi_t^h(j) - \Theta^h(j))P_t(j) \tag{2.11}$$

where τ_t is the number of hours in period t, $\pi_t^h(j)$ is the short-run marginal cost (SRMC) of the hydrothermal electrical system to which power plant j contributes (US\$/MWh), $\Theta^h(j)$ is the O&M cost of hydropower plant j (US\$/MWh), and $P_t(j)$ (MW) is the power generated by hydropower plant j during period t.

The second term on the right hand side of Equation(2.10) is the net benefits from irrigation, which is the sum of the benefits $(\zeta_{t_f}^{(p)})(d)$ obtained for each crop p at each irrigation demand site d at the last stage t_f of the irrigation season. The net benefit at a given irrigation site is proportional to the volume of water, $y_{t_f}^p(d)$, that has been delivered to crop p at that site during the irrigation season :

$$IR_t = \begin{cases} \sum_{d,p} \zeta_{t_f}^p(d) y_{t_f}^{(p)}(d) & \text{if} \qquad t = t_f \\ 0 & \text{if} \qquad t \neq t_f \end{cases} \tag{2.12}$$

The net benefit function $\zeta_{t_f}^p(d)$ associated with crop p at site d is calculated as:

$$\zeta_{t_f}^p(d) y_{t_f}^p(d) = \left[\pi^p(d) c^p(d) - \theta^p(d)\right] A^p(d) \tag{2.13}$$

where $\pi^p(d)$ [US\$/T] is the farm gate price of crop p at site d, $c^p(d)$ [T/ha] is the actual yield of crop p at site d, $\theta^p(d)$ [US\$/ha] is the production costs of crop p at site d, and $A^d(d)$ [ha] is the maximum area that can be cultivated for crop p at site d. The impact of a variation in water supply (deficit) on crop yields is assessed using a linear relationship between crop yield deficit and the actual evapotranspiration (ET_a) (Allen et al., 1998). The state vector of SDDP includes the variable y_t, which can be considered as a "dummy" reservoir that must be refilled during the irrigation season (and depleted at the end). The continuity equation for this "dummy" reservoir is :

$$y_{t+1} - \boldsymbol{\epsilon} \ i_t = y_t \tag{2.14}$$

where i is the vector of irrigation withdrawals and ϵ is the vector of irrigation efficiencies.

The upper and lower bounds of these reservoirs are defined as :

$$\underline{y}_{t+1} \leq y_{t+1} \leq \overline{y}_{t+1} \tag{2.15}$$

The "dummy" reservoir is then depleted at the end of the season (stage t_f) when crops are harvested and sold. Constraints imposed on irrigation withdrawals at stage t ensure that the allocation decisions are consistent with the capacity of the conveyance system or pumping station and with crop water requirements at that stage :

$$\underline{i_t} \leq i_t \leq \overline{i_t} \tag{2.16}$$

After convergence on the expected benefits from water allocation over the selected planning period, the model provides a number of results for each time step at key locations throughout the basin (reservoirs, irrigation demand sites, power stations, river reaches) such as the outflows from the turbines, spillage, storage levels and evaporation losses from the reservoirs, irrigation withdrawals, irrigation return flows, river discharges, at-source and at-site marginal water values (corresponding to the dual variables (Lagrange multipliers) associated with the mass balance equation (Equation 2.6), net benefits/costs, etc. As many simulations are carried out, it is possible to construct an empirical statistical distribution for each result.

2.2.2 Bankruptcy methods: Equitably sharing the benefits

In the methodology, described in detail in **Paper II**, water is efficiently allocated among resource users in a river basin, by the RBA. The economic benefits of cooperative water use are then redistributed over the basin to ensure equity. Equity, however, may be considered as value judgements and may not have the same definition from one river basin to another. Analytical methods may be useful for determining the meaning of equity in specific cases, and one that has been developed to share scarce resources is the bankruptcy method. As discussed in Section 1.2.1 the aim of this method is to distribute an asset to a group of creditors when the amount of the asset is insufficient to satisfy the total claims of all creditors. Over the years, a number of rules have been developed to solve this type of problem. These alternative solutions are derived using an axiomatic approach and are characterized in terms of the properties that express the different value judgements upon which the definition of fairness, for the rule, is based.

The most used rules in the library of bankruptcy rules are the *proportional rule* (PRO) in which division of the award is based on equal proportions of the claims, the *constrained equal awards* rule (CEA) which is based on equal division of the award itself, and the *constrained equal losses* rule (CEL) which is based on the equal division of losses (difference between the award and the total claims). These three bankruptcy rules have strong theoretical and empirical support (Ansink and Marchiori, 2010) and a long tradition in history (Herrero and Villar, 2001). Herrero and Villar (2001) have called these sharing rules the "three musketeers" because they are the most common methods of solving practical problems and they are the only three rules that satisfy an intuitively reasonable set of axioms including the equal treatment of equals.

The PRO rule, the most common of the rules, has been applied in resource allocation problems such as the sharing of water in the Murray-Darling River (National Water Commission, 2011) and the allocation of fish stocks in New Zealand and Canada (Connor, 2001; Sporer, 2001). All three of these rules have been applied in many practical studies in the allocation of natural resources. Along with their use in water allocation problems, described in Section 1.2.1, they have been used to determine the fair allocation of oil and gas resources in the Caspian Sea (Sheikhmohammady, Kilgour and Hipel, 2010) and the distribution of the Total Allowable Catch (TOC) in the North European anglerfish fishery (Gallastegui, Inarra and Prellezo, 2002) and the Northeast Atlantic Norwegian cod fishery (Inarra and Skonhoft, 2008).

2.2.3 Common bankruptcy rules

In a bankruptcy problem, the net worth of the estate (good or resource) is denoted by E. The set of agents is N, and each agent $j \in N$ has a claim $c_j \geq 0$ on E. The vector of claims of all agents is denoted as $c = (c_j)_{j \in N}$ and $C = \sum_{j \in N} c_j$ is the total claims of all agents.

In a claims problem there is a pair (c, E) in which $C \geq E$. A solution to the claims problem is a function F (or rule) that associates, with the problem, a division of the estate between the claimants, with the following properties: (i) $0 \leq F(c, E) \leq c$ and (ii) $\sum_{j \in N} F_j(c, E) = E$.

The proportional (PRO) rule awards the estate proportional to the claims of the agents. That is, it equalizes the ratios between claims and awards. The formal definition is as follows: for all (c, E) there exists a $\gamma > 0$ such that $PRO_j(c, E) = \gamma c_j$ and, by definition, $E/C = \gamma \in]0, 1]$.

The constrained equal awards (CEA) rule divides the estate equally between all claimants with the restriction that no agent receives more than their claim. For all (c, E) and all $j \in N$ there exists a $\gamma > 0$ such that $CEA_j(c, E) = min\{c_j, \gamma\}$, implying that γ solves $\sum_{j \in N} min\{c_j, \gamma\} = E$.

The constrained equal losses (CEL) rule distributes the estate in such a way that all agents suffer the same losses, subject to the condition that no agent gets a negative reward. For all (c, E) and all $j \in N$ there exists a $\gamma > 0$ such that $CEL_j(c, E) = max\{0, c_j - \gamma\}$, which implies that γ is such that $\sum_{j \in N} max\{0, c_j - \gamma\} = E$.

Note that the idea of equality underlies each of the above rules. However, each rule applies the idea of equality to different variables. The PRO rule emphasizes the equality of the ratios, the CEA rule ensures the equality of the awards and the CEL rule focuses on the equality of the losses.

An example of the application of these three rules is shown in Table 2.1. In this example, there are 4500 units to share ($E = 4500$) and each of 3 claimants have the following claims to the estate: (i) 500 units, (ii) 2000 units and (iii) 3500 units.

Table 2.1: Example application of the PRO, CEA and CEL rules.

Claimant	Claim	PRO(1)	CEA(2)	CEL(3)
1	500	375	500	0
2	2000	1500	2000	1500
3	3500	2625	2000	3000

(1) PRO: $\gamma = E/C = 4500/6000 = 75\%$. Each claimant gets 75% of its claim.

(2) CEA: In step 1 the smallest claim is satisfied (claimant 1). In the next step the next smallest claim is satisfied (claimant 2). The rest of the estate is given to claimant 3.

(3) CEL: The difference between the total claims (6000 units) and the estate (4500 units) is divided equally among the claimants. Each claimant gets 500 units less than its claim.

Herrero and Villar (2001) present the three classical solutions to bankruptcy problems (along with the Talmud rule) and provide a comparative analysis of these from an axiomatic point of view.

A joint characterization of the three rules highlights their common features and supports these rules as leading candidates in the resolution of bankruptcy problems. The common features include *equal treatment of equals*, *scale invariance*, *composition*, *path independence* and *consistency*. The first property has an ethical content while the others can be regarded as procedural requirements, preventing the solution of the problem from being dependent on the choice of units or the agenda, or from being unstable with respect to subgroup renegotiations. Herrero and Villar (2001) describes these properties in detail. They also compare the three rules in terms of a single differential property, facilitating the selection of the rule depending on the nature of the problem being considered, with each rule being regarded as implementing a specific notion of fairness. These properties are *exemption*, *exclusion* and *self-duality*.

The CEA rule supports the principle of exemption and is appropriate for problems in which the primary concern is the individual claimant, by assuming that claims that are relatively small should be fully honoured. As a result, agents with smaller claims get a relatively higher amount of satisfaction from their share of the estate.

The property of exclusion underlies the CEL rule and states that those agents with minor claims should be disregarded. In other words, the claims are more important than the individual claimants. In this case, agents with larger claims are given priority in the distribution of the estate.

The PRO rule lies between these two, giving priority to neither smaller or larger claims. Claims and claimants are treated equally. The distinctive property of the proportional rule, compared to the other two rules, is that it is self-dual. The property of self-duality indicates that the solution is symmetric with respect to awards or losses.

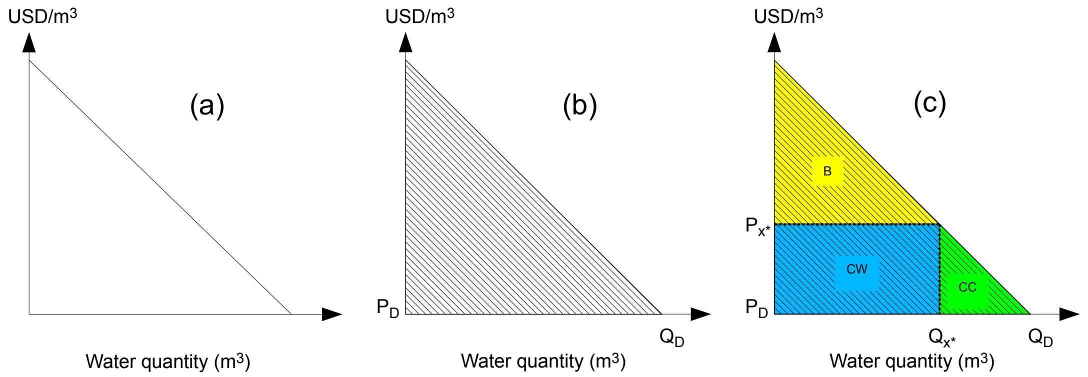


Figure 2.4: Demand curve.

2.2.4 The ECO rule for sharing benefits

In the methodology described in **Paper II**, users must pay for the water that is allocated to them and the total of these payments, over the basin, are collected and redistributed back to the water users according to the ECO rule.

The determination of the estate (E) and the claims of the agents (c_j) are illustrated in Figure 2.4. Figure 2.4(a) shows the water demand curve for a water use agent in a river basin. The marginal value of water for this particular water user is the value associated with one more unit of water and is determined by the user's willingness to pay for this additional unit. This willingness to pay is described by the demand curve. In a scenario in which there is no water scarcity, the water will be used up to the maximum required by the user for their particular use. This is the quantity (Q_D) in Figure 2.4(b) where the demand curve crosses the horizontal axis. As well, users do not pay for water because the marginal value of water when there is no scarcity is 0 (therefore $P_D = 0$). The net benefits for the water user is calculated as the area under the curve, above the price paid by the user (the consumer surplus) and is shown on Figure 2.4(b) as the shaded area. In a situation of water scarcity, in which water is efficiently allocated, and the water user must pay for water, the consumer surplus is shown in Figure 2.4(c) as area B. In this figure, Q_{x^*} is the amount of water allocated to the user and P_{x^*} is the social cost of water.

The difference between the consumer surplus in the two scenarios is composed of 2 different costs: the cost of water (area CW in Figure 2.4(c)) and the cost of cooperation (area CC in Figure 2.4(c)), which is defined as the amount of benefits lost to an agent through the cooperative allocation of water to ensure economic efficiency. The total of these costs is the claim for the water user ($c_j = CW_j + CC_j$). The estate (E) is the total of water costs collected over the basin ($E = \sum_j^N CW_j$). Since the total claims over the basin is $C = \sum_j^N CW_j + \sum_j^N CC_j$, this is a bankruptcy situation.

The common bankruptcy rules presented previously (PRO, CEA and CEL) do not take into account that water use agents in the river basin already receive an amount of benefits from the use of water allocated to them (area B in Figure 2.4(c)) and that, in fact, the final benefits for an agent is made up of the benefits from water use and the benefits obtained from the allocation of the estate to the agents.

The new sharing rule, based on bankruptcy theory was developed to take into account the total value of the benefits to the water users, for the case study, specifically.

The first step in the development of this rule was to define the meaning of "equitable" for the case study basin. As described in **Paper II**, this definition should be determined in negotiation with water users in the basin to increase the chance of cooperation between the agents who, in the end, should be in agreement on how the benefits are shared. As it was beyond the scope of this project, the definition of equity, and the properties underlying the sharing rule, were not determined with stakeholder input but, rather, as an objective viewpoint.

The properties defining equity are:

- **Feasibility.** This is the requirement that the sum of the benefits shared not exceed estate;
- **Non-negativity.** This is the requirement that each agent receive a non-negative amount;
- **Claims-boundedness.** This requires that each agent should receive, at most, the amount of its claim;
- **Solidarity.** This is a requirement that all agents take equal responsibility for the shortfall in benefits, at certain nodes, due to the efficient economic allocation of water over the basin;
- **Security of minimum benefits.** This requirement states that the benefits obtained from the use of water allocated to each agent are uncontested.

The first three properties are well-defined in the bankruptcy literature. The last two properties are specific to the problem being studied.

In Figure 2.4(c), area B is the final net benefits (FNB) received by the agent through the use of water allocated to it. The benefits expected (ENB), if there was no water scarcity, is the total of areas B+CW+CC. The initial proportion of the ENB that the user receives is FNB/ENB. This is the minimum amount of benefits that the user will receive, ensuring the property of security of minimum benefits.

In Figure 2.5, area b represents the amount of the estate that is allocated to an agent. Therefore, the total final benefits of the agent is equal to $FNB + b$. To ensure the property of

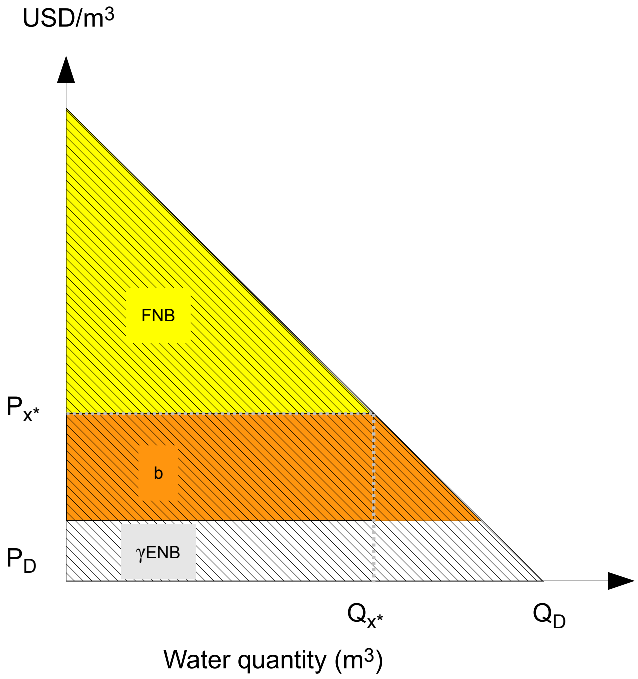


Figure 2.5: Demand curve for ECO rule.

solidarity, each user should receive a portion of their claims (area b) to guarantee that the final ratio ((FNB+b)/ENB) is the same for all users. In other words, each user will pay the same proportion (γ) of their ENB to cover the cost of cooperation.

The ECO rule is defined as:

$$b_j^{ECO} = ENB_j - (FNB_j + \gamma ENB_j) \tag{2.17}$$

where γ is chosen such that :

$$\sum_{j=1}^{J} b_j^{ECO} \leq E \tag{2.18}$$

and:

$$b_j^{ECO} \geq 0 \tag{2.19}$$

$$b_j^{ECO} \leq c_j \tag{2.20}$$

Equation 2.17 defines the benefit for each agent (b_j^{ECO}) as the difference between an agent's expected net benefits (ENB_j) and its final net benefits (FNB_j) plus a certain proportion of the expected net benefits. This proportion is defined as:

$$\gamma = (ENB_j - (FNB_j + b_j^{ECO}))/ENB_j \tag{2.21}$$

where γ is the same for all agents.

Equation 2.18 defines the upper limit of the total benefits allocated to all agents (the property of *feasibility*) and Equations 2.19 and 2.20 define the lower and upper limits for the benefits allocated to each water user (the properties of *non-negativity* and *claims-boundedness*).

As mentioned in Section 2.1 each river basin will have a different definition of fairness, as determined in collaboration with water users, and, as a result, each river basin is likely to have its own unique sharing rule. It should be noted that the rule, described above, was not developed with stakeholder input, as this was beyond the scope of the PhD project. The motivation for using this rule is that the cost of cooperation is divided equally among the agents (as an equal percentage of their ENB). This may not, in reality, be the solution to sharing benefits in the case study. Rather, this is an example of how the method for sharing benefits may work when applied to a river basin. This, however, does not weaken the impact of the methodology, as the point of view is objective and the analysis is a benchmark or reference point.

In summary, an institutional arrangement, overseen by an RBA, with full cooperation between water users assumed, is presented. The arrangement couples efficient water allocation with the equitable sharing of the benefits of water use in an auction-based market system. In this thesis, the methodology is applied to the Eastern Nile River Basin. This case study was chosen for a number of reasons. A full set of data for input into the hydro-economic model is available for this case study. As well, not only is the basin closed, especially when environmental needs are factored in, but it currently has major infrastructure being built (GERD) and plans for future hydropower and irrigation development. The Eastern Nile River Basin also has a long history of non-cooperation and current water allocation is based on colonial era bilateral agreements that designate Egypt and Sudan as the only beneficiaries of the Nile waters. Future cooperation is imperative in this basin to take advantage of hydropower potential in Ethiopia and the agriculture potential in Sudan, as well as to mitigate, as much as possible, the effects of climate change in the near future. A detailed description of the Eastern Nile River Basin can be found in the next chapter.

Chapter 3

Case Study

Historically, the Eastern Nile River Basin has been characterized by complex environmental, political, social and economic challenges such as food insecurity, extreme poverty, floods, droughts, environmental degradation and conflicts over the control and use of the basin water resources. As a consequence, there is international recognition for the need to manage and protect the resources of the basin. The cooperative management of the Eastern Nile River Basin is an important catalyst for the economic and political integration, but remains one of the great challenges in transboundary river basin management.

This chapter provides an overview of the Eastern Nile River Basin, including the availability and use of water in the basin and the current policies governing water allocation.

3.1 Eastern Nile River Basin

3.1.1 Physical context

General description

The Nile River, one of the most important waterways in the world, ensures the livelihood of the more than 240 million people that inhabit its basin (NBI, 2012), living in 11 different countries: Burundi, DR Congo, Egypt, Ethiopia, Kenya, Rwanda, South Sudan, Sudan, Tanzania, Uganda and Eritrea. This main, vital water artery, located in the northeast region of Africa, is more than 6800 km in length, with a basin covering a total area of more than 3 million km^3 (or about 10% of the African continent). Two main tributaries, the Blue Nile and the White Nile, merge at Khartoum, in Sudan, to form the Main Nile which ultimately discharges into the Mediterranean Sea (Figure 3.1). The White Nile originates in the Kagera River in Burundi and drains an area from Lake Victoria to Khartoum, passing through one of the most important wetlands on the planet, the Sudd. The Blue Nile starts in the highlands of Ethiopia, at Lake Tana, and flows northward through the plains of Sudan before merging with the White Nile at Khartoum. The Eastern Nile River Basin includes about one third of Ethiopia, a large

Figure 3.1: Nile River basin (Source: NBI (2012))

portion of Sudan and South Sudan and almost the entire cultivated and inhabited areas of Egypt, as well as a small part of Eritrea. The Eastern Nile River Basin is made up of the Blue Nile, the Atbara, the Baro-Aboko-Sobat, the White Nile downstream of Malakal and the Main Nile sub-basins (Figure 3.2). Runoff from the Blue Nile region contributes about 85% of the annual Nile flows (NBI, 2012).

Water availability

Rainfall over the Eastern Nile River Basin is characterized by uneven spatial and seasonal distribution (Figure 3.3). The basin experiences a single rainy season during the summer months, between June and October. The reliability and volume of precipitation declines moving northwards, with the basin region in Egypt and the northern region of Sudan receiving

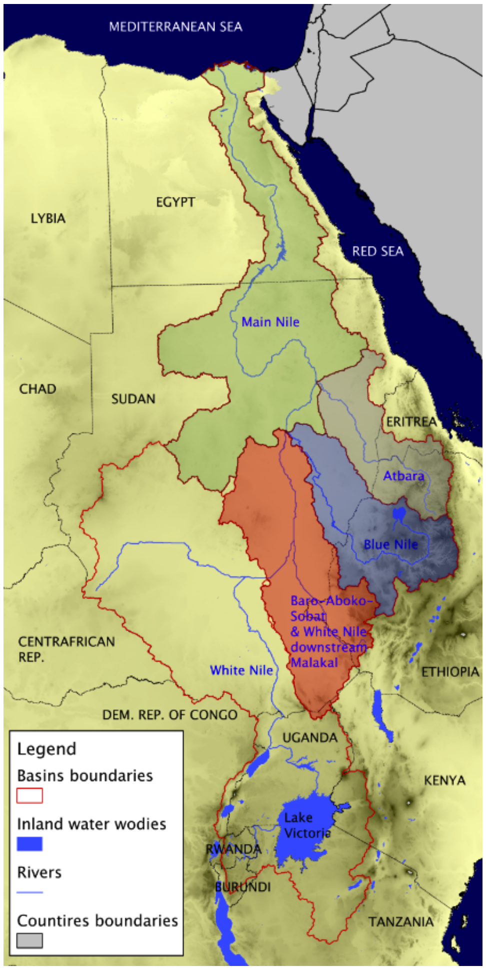
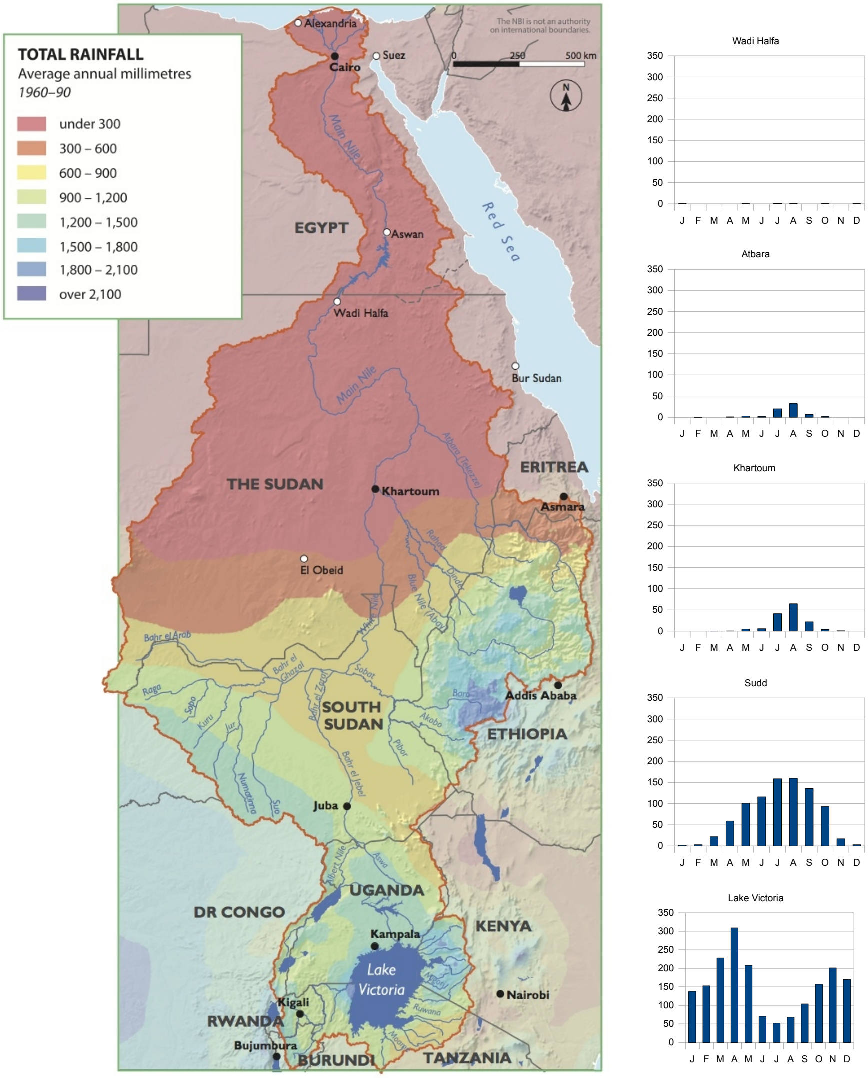


Figure 3.2: Eastern Nile River basin

insignificant annual rainfall and Ethiopia receiving between 1200 and 1600 mm (Bastiaanssen and Perry, 2009). At the same time, evaporation in basin increases moving northwards, with an annual loss of 10 to 15 km^3 of the Nile's water due to evaporation at Aswan (Wolters et al., 2016).

River flow increases from the upper catchment to the central part of the basin (Figure 3.4(b)), with the long term average discharge measured at Khartoum being about 95 km^3/yr. River abstractions, seepage losses and evaporation losses cause the river to lose water as it moves downstream. The mean annual discharge of the Main Nile River, as measured at Dongola in northern Sudan, is 87 km^3/yr (Conway, 2005). The long term average inflow into Lake Nasser is estimated to be 84 km^3/yr. Evaporation from Lake Nasser is about 10.5 km^3/yr.

Runoff is seasonal, occurring from July to November in the Blue Nile sub-basin, with only base flow for the remainder of the year (Figure 3.5). In the Atbara basin, all runoff is concentrated between July and September. In the Main Nile sub-basin, with no surface runoff contribution,



(Map prepared by the NBI; source of data: Climatic Research Unit)

Figure 3.3: Average rainfall (mm) at various sites in the Nile Basin (Source: map (NBI, 2012), data (Sutcliffe and Parks, 1999))

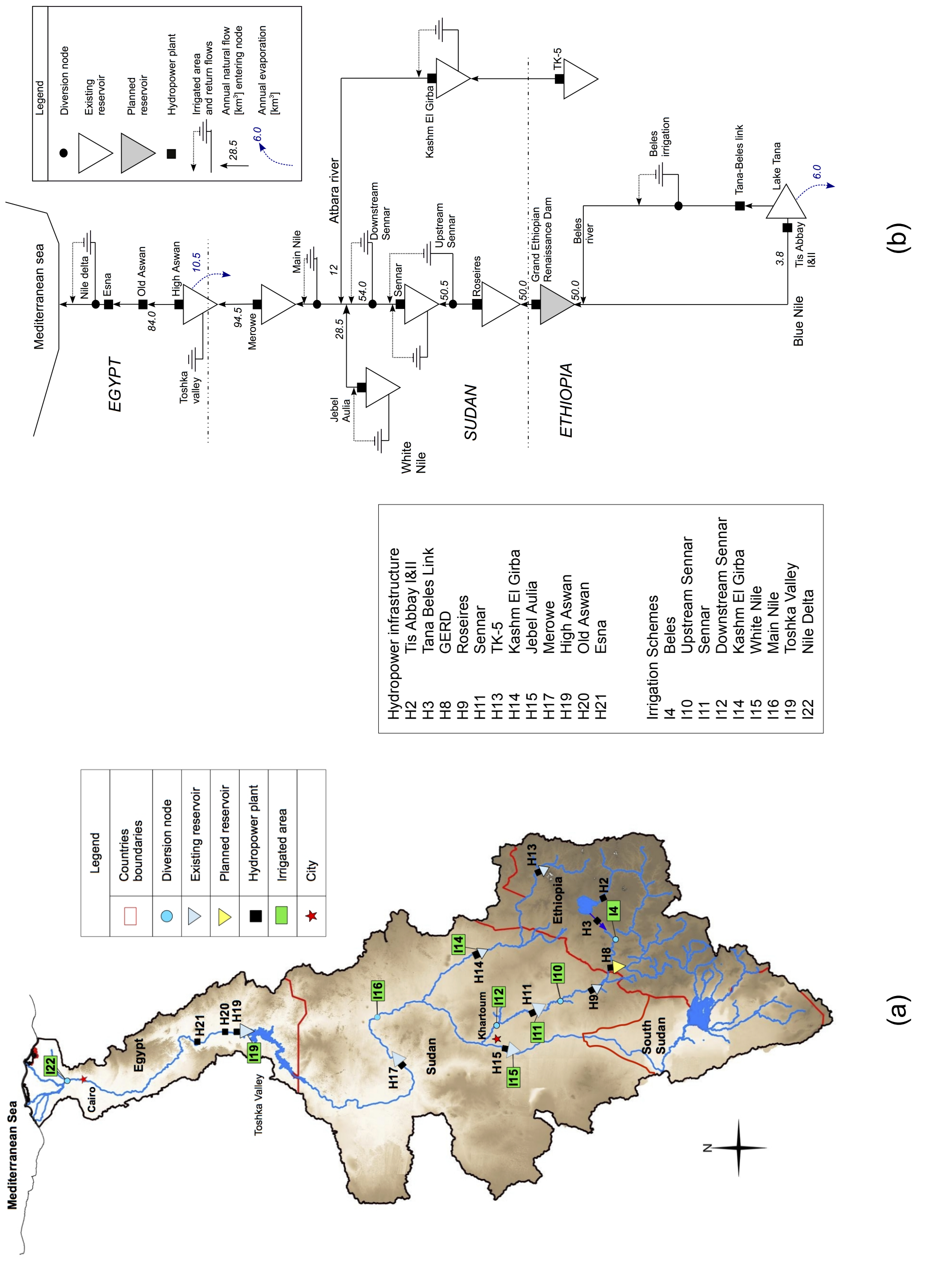


Figure 3.4: Eastern Nile River Basin, (a) Localization of hydropower infrastructure, (b) Topology of the system.

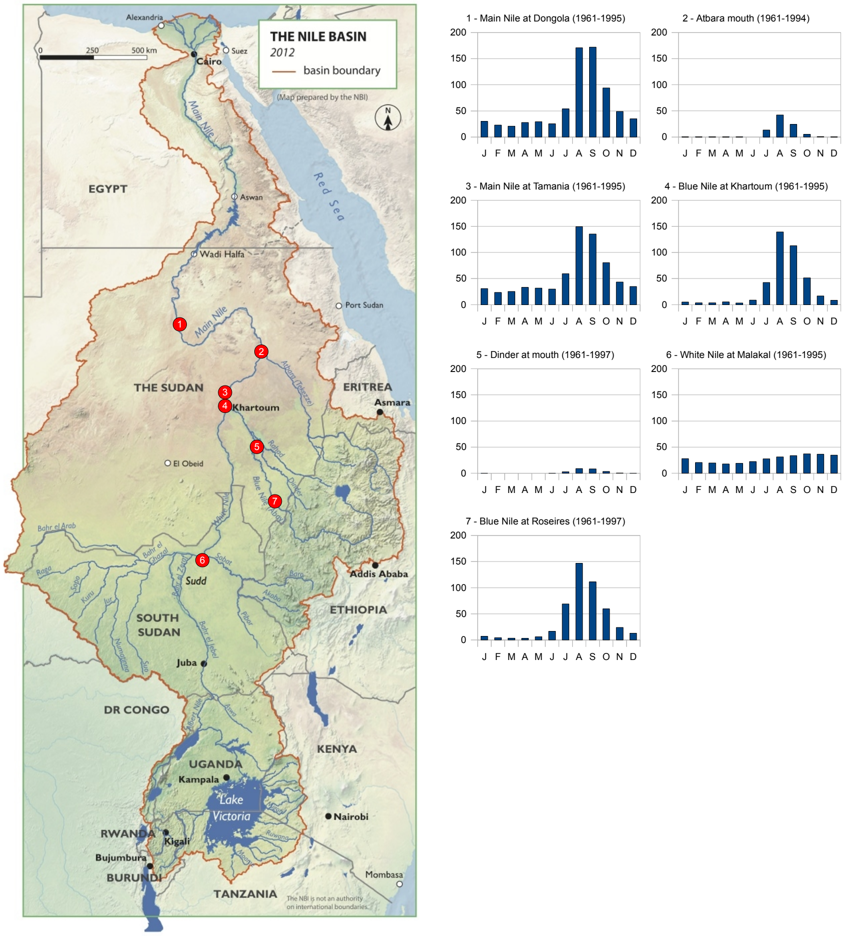


Figure 3.5: Average monthly runoff in the Eastern Nile River Basin (km^3) (Source: map (NBI, 2012), data (Sutcliffe and Parks, 1999))

in-stream flow losses result in a net loss to the overall Nile system.

Water contribution to the Nile River in the Eastern Nile River Basin is mainly from Ethiopia (85%). Egypt, on the other hand, provides no contribution to the system. Conversely, the arid and semi-arid regions of Egypt and Sudan show strong dependency on the Nile waters, as shown in Table 3.1.

3.1.2 Water use

The dominant uses of water in the Eastern Nile River Basin are irrigated agriculture and hydropower generation, mostly in Sudan and Egypt. This is, however, likely to change in the near future with the completion of the Grand Ethiopian Renaissance Dam on the border of Ethiopia and Sudan.

Table 3.1: Water dependency in the Nile River riparians (Data from (FAO, 2015))

Country	IRWR[1] (km^3/yr)	ERWR[2] (km^3/yr)	Dependency Ratio[3] (%)
Burundi	10.06	2.476	19.75
Rwanda	9.5	3.8	28.57
Tanzania	84	12.27	12.75
Uganda	39	21.1	35.11
Sudan	4	33.8	96.13
South Sudan	26	23.5	65.79
Egypt	1.8	56.5	96.91
Ethiopia	122	0	0
Eritrea	2.8	4.515	61.72
Congo	222	610	73.32
Kenya	20.7	10	32.57

[1] Internal renewable water resources is that part of the water resources (surface water and groundwater) generated from endogenous precipitation.

[2] External water resources as the part of a country's renewable water resources that enter from upstream countries through rivers (external surface water) or aquifers (external groundwater resources).

[3] That part of the total renewable water resources originating outside the country.

Hydropower Infrastructure

The Eastern Nile River system currently supports 11 major hydraulic infrastructures, which are listed in Table 3.2. Figure 3.4(a) shows their localization in the basin and the topology of the system (Figure 3.4(b)).

Ethiopia: With its high volume of water and steeply sloping landscape, Ethiopia has huge hydropower potential. There is an estimated 13,000 MW potential from the Blue Nile alone. Currently, Ethiopia has 4 completed infrastructures (CharaChara weir, Tis-Abay hydroelectric project, Tana-Beles scheme and TK-5 (Tekeze) Dam) and one currently under construction (Grand Ethiopian Renaissance Dam).

The TK-5 dam, on the Atbara-Tekeze River began operation in 2009. The dam is located on the border with Eritrea and provides a year-round supply of water downstream, along with 300 MW of generation capacity. The aim is to produce around 30% of the current total national electric production. On the Blue Nile, downstream from Lake Tana, The Tis-Abay I hydroelectric project began transmitting power in 1964. In 1997, the CharaChara weir was built to boost the power supply and, in 2001, another weir (Tis-Abay II) was commission to boost power by 20%. The Tana-Beles scheme, which went online in 2010 consists of an artificial link between the Lake Tana and the Beles river to generate hydroelectricity and to irrigate around 150,000 ha of land in the future.

Table 3.2: Nile basin infrastructure

Name	Country	River	Live storage [hm^3]	Capacity [MW]
Tis Abbay I/II	ET	Blue Nile	run-of-river	86
Tana-Beles link	ET	Blue Nile	run-of-river	270
GERD	ET	Blue Nile	79 000	6000
TK-5	ET	Atbara	9 200	300
Roseires	SU	Blue Nile	6 900	275
Sennar	SU	Blue Nile	480	15
Khashm El Girba	SU	Atbara	630	17
Jebel Aulia	SU	White Nile	2 800	30
Merowe	SU	Main Nile	8 300	1250
High Aswan	EG	Main Nile	105 900	2100
Old Aswan	EG	Main Nile	run-of-river	500
Esna	EG	Main Nile	run-of-river	90

In April 2011, Ethiopia began construction on the newest dam (the Grand Ethiopian Renaissance Dam). Located about 40 km from the border with Sudan, the dam is estimated to have a 5250 MW installed capacity and should be completed in 2017.

Sudan: In Sudan, the Sennar Dam (built in 1926) and the Roseires Dam (built in 1950) provide seasonal regulation of the Blue Nile in order to provide water for more than 1 million ha of crops in 3 major irrigation schemes. They also supply electricity to Sudan, but their production is small. A project to heighten and lengthen the Roseires dam was completed in 2013, which brought the storage capacity up to over 7 km^3. This helped to reduce flooding downstream and allowed for an additional 420,000 ha of irrigated land (Conniff et al., 2012). The Kashm El Girba Dam, on the Tekeze-Atbara River, was built in 1964 to irrigate the Al-Gerba agricultural scheme and to generate 70 MW of power. The design storage capacity of the reservoir at this site is about 10% of the inflow. High sedimentation in the reservoir, however, dropped the storage capacity by 50% as of 1977. This loss of storage capacity has resulted in severe water shortages during drought years and an associated decline in the crop area cultivated. Located on the White Nile, upstream from its confluence with the Blue Nile, the Jebel Aulia Dam is operated to reduce pumping costs for the irrigated areas around the reservoir. Finally, the Merowe Dam, at the fourth Nile cataract, was inaugurated in 2009. Not with controversy, including the displacement of 50,000 people and the destruction of a number of archaeological sites, the main purpose of the dam is to increase the Sudanese production of hydroelectricity with its installed capacity of 1250 MW. Not yet up to capacity, it currently generates about 5.5 TWh per year.

Egypt: The Aswan High Dam (AHD) is the largest infrastructure in the basin, until the GERD comes online. The AHD fully regulates the flow of the Nile in Egypt and, with its over-year storage and 2100 MW installed capacity, it was designed for reliable irrigation supply, to meet increasing energy demand (around 9% of the total national electricity production), to improve downstream navigation and to protect Egypt against flooding. Downstream from the AHD, the Old Aswan Dam is operated as a run-of-river plant which regulates, slightly, the daily outflows from the AHD and contributes to the production of electricity along with the downstream Esna run-of-river plant.

Irrigated Areas

Ethiopia: Ethiopia has 3.7 million ha of land that can be developed for irrigation (Tenaw and Awulachew, 2009). Half of this is in the Nile basin, but only 5-6% is actually under production (about 250,000 ha) of which less than 20,000 ha are in the basin. Due to steep slopes and deep valleys, the possibilities of irrigation, at a reasonable cost, are limited in the Ethiopian highlands. The proposed irrigation sites take water directly from around the Beles River, an area in which there are plans to develop 150 000 ha (Norplan, Norconsult and Lahmeyer International, 2006).

Sudan: Irrigation in Sudan is organized around 6 major schemes as shown in Figure 3.4. Along the Blue Nile, water is pumped for irrigation between Roseires and Sennar dams to irrigate around 300 500 ha of crops. The Sennar reservoir feeds the Gezira-Managil scheme, which is the largest in Sudan (870 000 ha) and the only gravity irrigation scheme along the Blue Nile. Water is also abstracted by pumps from the Blue Nile between Sennar and Khartoum to irrigate 74 500 ha . On the White Nile, about 180 000 ha are currently irrigated by water pumped from the Jebel Aulia reservoir. The New Halfa scheme (120 000 ha), located downstream from the Kashm El Girba reservoir, was established to resettle Sudanese farmers affected by the creation of Lake Nasser. The last significant scheme is located along the Main Nile, downstream of Khartoum, with 88 000 ha of cultivated area.

Egypt: Irrigated agriculture in the Eastern Nile River Basin is dominated by Egypt. The main area of irrigated agriculture is the Nile Delta. In 1997, the Toshka Lakes were formed when Egypt developed pumping stations and canals to send spillage from Lake Nasser into a depression in the southwest desert about 300 km to the west. The goal of the project was to develop new irrigation areas in Egypt. In 2010, Egypt's total water withdrawal was estimated at 78 km^3, 67 km^3 of which was dedicated to agriculture (86 percent). Of the 78 km^3, 84% (or 65.6 km^3) was sourced from primary and secondary surface water, almost all of which came from the Nile (97%). The actual water use by Egypt is widely believed to be in excess of the amount allocated under the 1959 agreement (FAO, 2015).

Irrigation potential in the country is estimated at 4.42 million ha. The total area equipped for irrigation in 2010 was 3.61 million ha, including 2.73 million ha (or 76%) in the Old Lands (Nile Delta and Nile Valley).

3.2 Existing policy and legal framework

There is a long history of unsuccessful negotiations over water allocation and development of the Nile water resources. Attempts at cooperation within the Eastern Nile basin go back to the early part of the 20th century.

One of the first treaties to cause tension between the riparian countries in the Eastern Nile River Basin was the "Treaty between Ethiopia and the United Kingdom, Relative to the Frontiers between the Anglo-Egyptian Sudan, Ethiopia, and Eritrea" in 1902 (Salman, 2013). As part of this treaty, Ethiopia engaged to not construct, or allow the construction of, any work across the Blue Nile, Lake Tana, or the Sobat which would stop the flow of water into the Nile, except in agreement with His Britannic Majesty's Government and the Government of the Sudan. This treaty has long been a source of conflict between Ethiopia on one side and Egypt and Sudan on the other. Ethiopia rejects the treaty, claiming that it was never ratified and that two versions of the treaty, in different languages, differ with respect to the article (Degefu, 2003). Egypt, on the other hand, insists that the treaty is valid and binding.

The 1929 Nile Waters Agreement between Britain (on behalf of its East African colonies, including Sudan) and Egypt was also a major source of conflict on the Nile basin. The treaty states that there will be no development in the Nile basin which could jeopardize the interests of Egypt, either by reducing the quantity or timing of water flowing into the country, without prior consent from Egypt. In the early 1960s, after gaining independence from Britain, the former colonies (Kenya, Uganda, Tanzania) argued that they were not bound to the treaty because they were not parties to it and invoked the Nyerere Doctrine which gave treaties that were agreed upon during the colonial era two years to be renegotiated, after which they would lapse if no new agreement was reached (Mekonnen, 1984). Egypt, on the other hand, invoked the principle of state succession, claiming that the 1929 agreement remained valid and gave them the power of veto over any Nile project that would jeopardize their interests (Tvedt, 2004).

Finally, in 1959, a new Nile Waters Agreement, called the "Agreement between the United Arab Republic and the Republic of the Sudan for the Full Utilization of the Nile Waters", was entered into force. This agreement established that the total annual flow of the Nile, measured at the Aswan Dam, was 84 km^3 and allocated this entire flow to Egypt and Sudan, with 55.5 km^3 going to Egypt and 18.5 km^3 to Sudan, leaving the remaining 10 km^3 for evaporation and seepage losses from the Aswan High Dam. As part of this agreement, the construction of the Aswan High Dam in Egypt and the Roseires Dam, on the Blue Nile in Sudan, were approved. The agreement also established the Permanent Joint Technical Committee (PJTC), made up of an equal number of members from each of the two countries, for the joint management of the Nile. Egypt and Sudan professed to recognize the claims of a share of the Nile waters of riparian states, if requested, but they reserved the right to have the final say on whether or not the states would get a share and, if so, how much. The PJTC was also to supervise the use of any granted water to other riparians. As part of this agreement, Egypt and Sudan claimed historic and established rights to the waters of the Nile.

The 1959 agreement has been fully rejected by the other upstream riparian countries who consider that the claim of Egypt and Sudan, to the entire flow of the river, infringes on their rights to a reasonable and equitable share of the Nile waters under international law. This claim is based strongly on the fact that the entire flow of the Nile originates within the territories of these upstream countries.

After Egypt's right to the water of the Nile was established in 1959, its power in the basin was reinforced. Egypt was able to gain access to international financial support for the development of projects while, at the same time, preventing upstream basin states from gaining similar support. Egypt demonstrated its need for water through the development of irrigation and hydropower infrastructure, at the same time preventing upstream countries from showing their need for the Nile waters. Advantages were tilted heavily in favour of Egypt and, minimally so, in favour of Sudan. The riparian countries upriver were completely excluded.

Over the next 3 to 4 decades there was a slow shift from complete Egyptian power toward a basin-wide cooperative effort. Joint technical projects meant to increase basin-wide trust and a prioritization of water policy in Ethiopia are two of the main factors leading to this shift away from Egyptian hegemony. These cooperative efforts started in 1967 with the HYDROMET project which focussed on the hydro-meteorological survey of the Equatorial Lakes region. The project was established by Egypt, Kenya, Sudan, Tanzania and Uganda with the purpose of understanding the hydrology of the region. Ethiopia, however, participated in the project as an observer because it did not believe that HYDROMET comprehensively encompassed the needs, interests, and concerns of all of the Nile basin riparians and it believed in basin-wide cooperation and that the most important undertaking should have been the preparation of a detailed framework of cooperation.

In 1983, Egypt fronted the UNDUGU agreement to establish the Nile Basin Economic Community. The intent was to involve all Nile riparians in projects that increased water flow into Egypt by improving infrastructure and augmenting water conservation. The agreement stated that Egypt and Sudan gained 50% of any water added through the initiative and that the remaining basin states could split the remaining water. This agreement was unsuccessful due to the wariness of upstream states to Egypt's goal of increasing its water quota.

The UNDUGA agreement was followed by the TECCONILE (Technical Cooperation Committee for the Promotion of Development and Environmental Protection of the Basin) in 1993. This was another initiative formed by Egypt and included Egypt, Sudan, Rwanda, Tanzania, Uganda and D.R. Congo. With international financial support, the committee prepared a "Nile Basin Action Plan" which envisioned 22 projects, of which very few were ever realized as a result of financial constraints and disagreements among the basin states. Once again, the main issues of water use and management in the Nile basin were not resolved to the satisfaction of all riparian states, especially so Ethiopia.

Despite the efforts of the HYDROMET, UNDUGU and TECCONILE projects, these never went beyond the attempts at improving communication between the riparian countries.

Policy attempts toward cooperation

In 1999, with the support of the World Bank and the UNDP, a more formal setting for cooperation among the Nile basin riparians, called the Nile Basin Initiative (NBI), was officially established. All Nile riparian states became members of the NBI, except Eritrea, which opted for being an observer.

The NBI is established as an intergovernmental organization, and has been viewed as a transitional arrangement to foster cooperation and sustainable development of the Nile River for the benefit of the inhabitants of those countries. It was able to bring together, for the first time, the (at that time) 10 riparian states at the ministerial level. It is guided by a shared vision "to achieve sustainable socio-economic development through equitable utilization of, and benefit from, the common Nile Basin water resources" (NBI, 2012).

The main objective of the NBI has been to conclude a cooperative framework agreement that would incorporate the principles, structures and institutions of the NBI and that would be inclusive of all of the Nile riparians. Work on the Nile Basin Cooperative Framework Agreement (CFA) started immediately after the NBI was formally established, and continued for more than 10 years. However, the process ran into some major difficulties as a result of the hardening of the respective positions of the riparians over the colonial treaties, as well as the Egyptian and Sudanese claims to what they see as their acquired uses of and rights to the Nile waters.

As of 2011, 6 riparian states had signed the agreement (Ethiopia, Tanzania, Uganda and Rwanda, Kenya and Burundi).

The CFA lays down some basic principles for the protection, use, conservation and development of the Nile basin. The CFA establishes the principle that each Nile basin state has the right to use, within its territory, the waters of the Nile River basin, and establishes a number of factors for determining equitable and reasonable utilization. In addition to the factors enumerated in the UNWC, the CFA includes the contribution of each basin state to the waters of the Nile River system, and the extent and proportion of the drainage area in the territory of each basin state.

The Nile today

Recent changes in the geopolitical balance have continued to challenge the sustainability of the status quo with respect to cooperation in the Nile River basin.

South Sudan gained its independence in 2011 and the geopolitical balance in the Nile River basin changed. Two months after its independence, South Sudan began efforts to join the NBI and was admitted as a full member in 2012. The South Sudanese government currently controls 28 per cent of the Nile's flow, however, it is likely that this allocation will require renegotiation between South Sudan and Sudan.

In 2011, the Ethiopian government announced plans for the construction of the Grand Ethiopian Renaissance Dam on the Blue Nile east of its border with Sudan. Construction is expected to be completed in 2017 on what will be Africa's largest hydroelectric power plant. After initial disapproval by Egypt (and Sudan to some extent), in early 2015 a declaration of principles on the dam was signed by the three riparians. This agreement approved the construction of the dam, but, at the same time, called for technical studies to be performed, aimed at safeguarding the water quotas for the three states. At the end of 2015, it was announced that Ethiopia, Sudan and Egypt had reached a consensus to put the provisions of the declaration of principles into practice by agreeing to the hiring of consulting firms that would conduct impact studies on the dam.

3.2.1 Future challenges

Egypt's current population of 85 million is growing at a rate of almost 2%/yr and is expected to reach 140 million by 2050. This rise in population will increase the demand on water resources that are already being overused, with the UN warning that Egypt could run out of water by 2025 (Nunzio, 2013).

Water shortages and a lack of arable land means that food security in Egypt is already at risk. To mitigate this risk, Egypt has started land reclamation schemes in the desert, which will require even greater amounts of water. Already using 80% of the nation's water supply, the agricultural sector will add even more pressure on the energy sector in the country. With about 10% of the country's electricity generation capacity coming from the Aswan High Dam, unless Egypt overhauls its inefficient water networks (including the cultivation of high water-use crops such as sugar cane and rice, miles of irrigation canals in need of repair or updating that lead to significant evaporation and seepage losses, and surface irrigation techniques that contribute to high evaporation), it will experience a major water crisis in the near future. And, as strategic alliances among upstream countries strengthen, allocation of water to Egypt is likely to decrease, or at least stay the same as it currently is.

Populations are also rapidly expanding in upstream riparians. This population growth, along with increased economic growth has, and will, stimulate the development of water infrastructure projects upstream in the Nile basin. In Ethiopia alone, a population growth of 2.9%/yr and economic growth averaging 7.5%/yr (between 2010 and 2013) has led to an increase in the demand for projects. As other upstream riparians also experience economic growth, the demand for projects will increase, possibly leading to reduced flows downstream as well as land degradation. And population growth, in itself, will exacerbate environmental issues such as an increase in wastes from municipal, industrial and agricultural sectors.

The independence of South Sudan has also increased pressure in the basin by forcing the reallocation of Nile water between the two nations of the former Sudanese territory. This could also have detrimental downstream effects on Egypt as South Sudan looks at infrastructure development along the Nile.

Finally, climate change will undoubtedly present serious challenges to food and energy security in the basin. Changes in temperature, precipitation and evaporation will lead to uncertainty in river flows, increases in the strength and frequency of droughts and floods, and potential shifts in rainfall seasons (McSweeney et al., 2010). There is also a strong possibility that climate change will result in a rise in sea levels which poses a very large risk for Egypt. The Nile Delta is highly populated, and is an industrially and agriculturally important region. According to Dasgupta et al. (2009), Egypt is among the top ten most impacted developing countries with a 1-m sea-level rise scenario having major impacts on population, GDP, wetlands and, especially, agricultural land.

3.3 Hydro-economic model of the Eastern Nile River Basin

The hydro-economic model used for the various activities in this PhD project included all major reservoirs, hydropower plants and irrigation schemes in the Eastern Nile basin (Figure 3.4(b)).

For **Activity #1**, four different management and development scenarios were created, representing either different levels of development of the river basin, in terms of water usage, or alternative management strategies/arrangements (Table 3.3). In the case of the development scenarios (scenarios 1, 2 and 4 below), full cooperation is assumed, meaning that there is coordinated operation of all basin infrastructure to optimize the total basin-wide economic benefits. The alternative management scenario (scenario 3 below) represents an intermediate level of cooperation.

The baseline scenario (S1) in which infrastructure and irrigation schemes are as currently found in the basin (see Figure 3.6(a)). This scenario assumes that the hydropower production is coordinated at the basin scale, however, individual countries still give priority to agricultural uses.

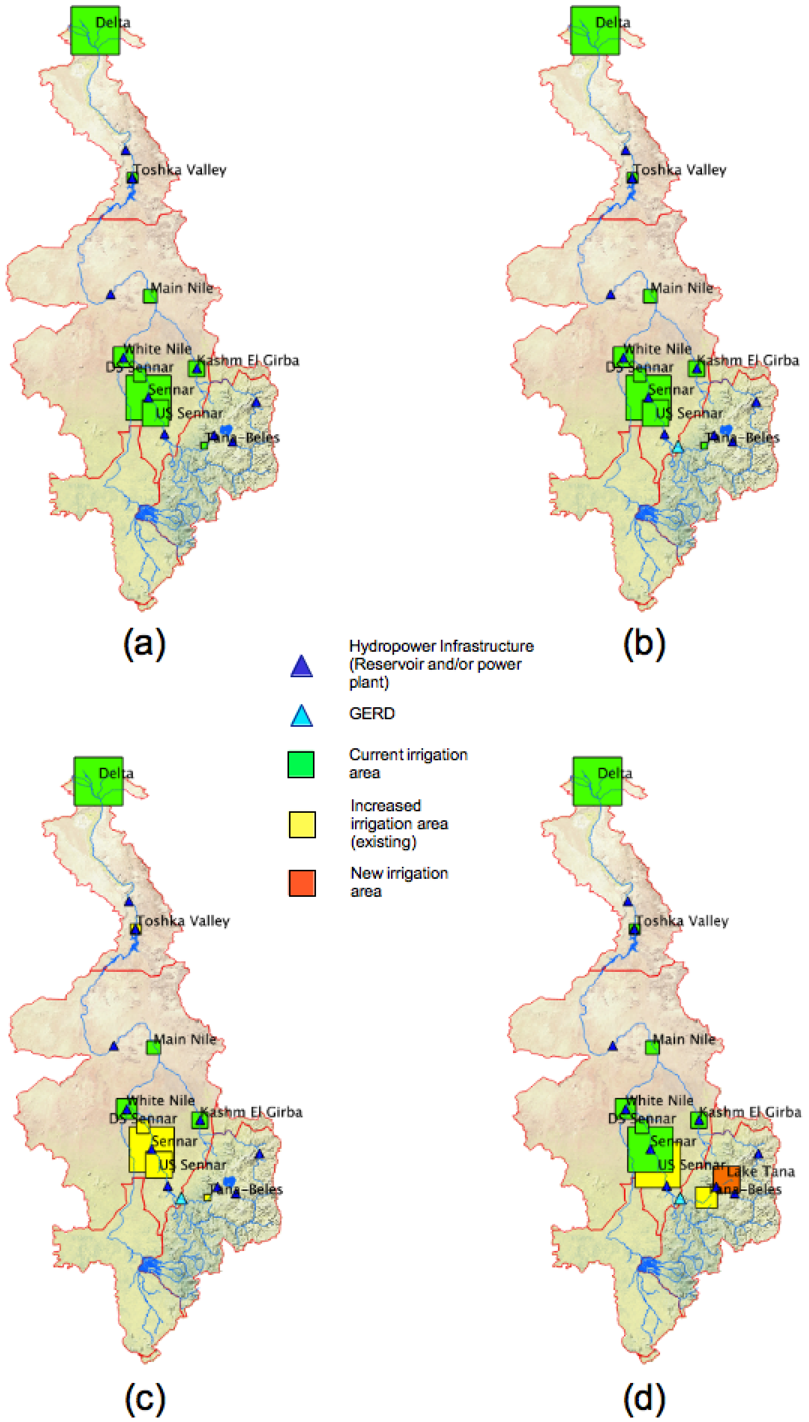


Figure 3.6: Scenarios investigated for the Eastern Nile River Basin. (a) Activity #1 - Scenario 1: baseline irrigation/hydropower scenario; (b) Activity #1 - Scenarios 2/3: GERD online; (c) Activity #1 - Scenario 4: GERD online, increased irrigation areas; (d) Activity #2: GERD online, increased irrigation areas.

A future scenario (S2) differs from S1 in that the GERD is online with all other parameters remaining the same (Figure 3.6(b)). Comparing this scenario to the baseline scenario shows the impacts of the GERD on the rest of the system, particularly on the agricultural and energy sectors in Sudan and Egypt.

A third scenario (S3) which corresponds to a situation in which the GERD would be operated to maximize energy revenues in Ethiopia only, regardless of downstream water demands is analyzed. This scenario uses the same parameters as in S2. Comparing this scenario to S2 shows the extent of the risk (and the cost) faced by downstream countries in the case of the unilateral operation of the GERD.

Finally, a second future scenario (S4) in which the GERD is online and there is an increase in the existing irrigation areas in Sudan and Ethiopia (Figure 3.6(c)), to reflect future irrigation plans in Ethiopia and Sudan, is analyzed. Comparing S4 to S2 indicates, among other things, the hydrologic risk exposure of Egypt to upstream withdrawals. This comparison, contrasted with the comparison between S1 and S2, determines whether the GERD attenuates or exacerbates the impacts.

Table 3.3: Management and development scenarios for Activity #1

Scenario	Irrigation Area	Hydropower Infrastructure	Cooperation?
S1	Current	Current	Yes
S2	Current	Current+GERD	Yes
S3	Current	Current+GERD	No
S4	Increased	Current+GERD	Yes

In **Activity #2**, the GERD is online and irrigation areas reflect a possible future scenario, including an increase in existing irrigation areas in Sudan and Ethiopia, and added irrigation areas around Lake Tana (Figure 3.6(d)).

Given the lack of accurate data with respect to irrigated agriculture in the basin, a horizontal demand curve for irrigation water withdrawals is assumed with a net return of 0.05 US$/m^3, as in Whittington, Wu and Sadoff (2005); Blackmore and Whittington (2008), and a seasonal short-run marginal cost (SRMC) averaging 80 US$/MWh for firm power and 50 US$/MWh for secondary power, which remains identical for all countries is used. These values are consistent with the feasibility studies of the hydroelectric dams in Ethiopia and international experience (Whittington, Wu and Sadoff, 2005; Blackmore and Whittington, 2008).

The model solves the water resources allocation problem using a monthly time step. To deal with the multi-year storage capacity of some of the reservoirs, a planning horizon of 10 years (T=120 months) was used. The analysis was carried out on year five results only. This ensures a "steady-state" condition that is not influenced by the initial hydrological and storage conditions or by the "end-effect" distortion as a result of reservoir depletion that happens as the end of the planning period approaches (Tilmant and Kelman, 2007).

Sources of data include feasibility studies of the GERD, other hydropower plants and Lake Tana. Infrastructure data were obtained from various sources, including ENTRO, relevant ministries in the Eastern Nile region (Ethiopia, Egypt, Sudan) and consultants reports. The existing model from the PhD project of Quentin Goor (Goor et al., 2010) was used. The information was updated for this project with the addition of the GERD and updated irrigation data.

3.4 Hydrological model

The SDDP-derived optimal benefit-to-go functions F_{t+1} were simulated using 30 different synthetically generated hydrologic sequences over the 120 month period. Historical flows were not used because of the limited length of concurrent flows at all stations (21 years). The available lateral inflows for each reservoir were used to estimate the parameters of a built-in multi-site periodic autoregressive hydrological model which were then used to generate the 30 hydrological sequences (Figure 3.7) .

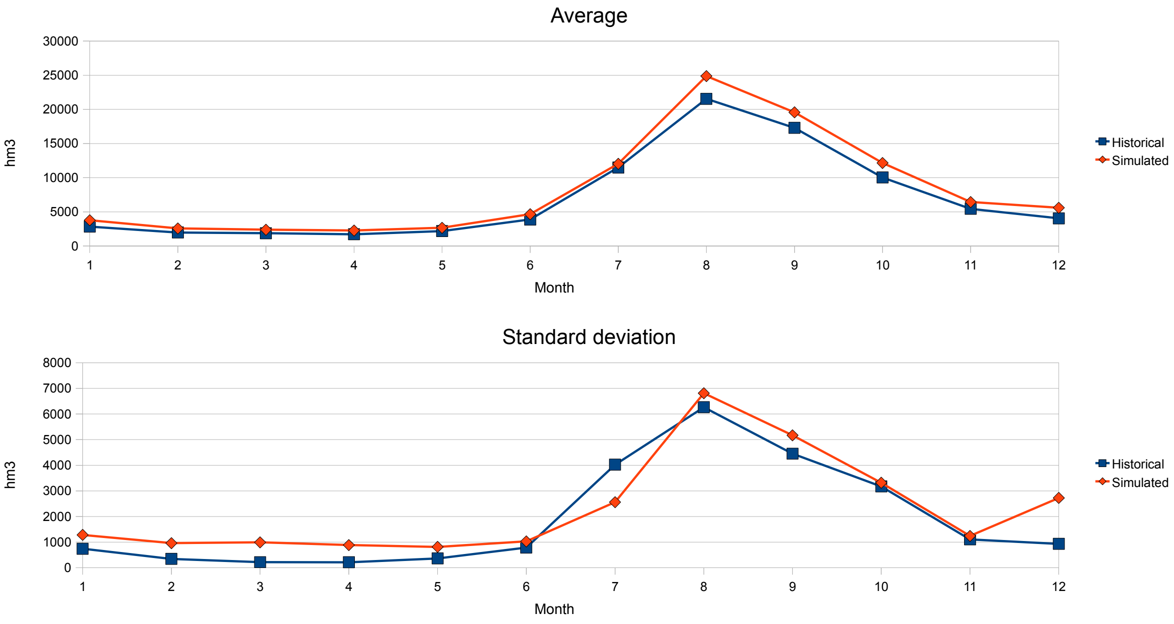


Figure 3.7: Parameters of the periodic autoregressive hydrological model - historic vs. simulated.

Assuming that the periodic process can be modelled by an autoregressive model of order 1, the model, for period t, can be written as:

$$q_t = \mu_{q,t} + \phi \frac{\sigma_{q,t}}{\sigma_{q,t-1}} (q_{t-1} - \mu_{q,t-1}) + \sigma_{q,t} \epsilon_t \tag{3.1}$$

where $\mu_{q,t}$ and $\sigma_{q,t}$ are vectors (size 1 x J) of the periodic mean and standard deviation of the current period reservoir inflows q_t, ϕ_t is the vector (size 1 x J) of periodic autoregressive parameter of order 1 and ϵ_t is a time independent (but spatially correlated) stochastic noise of zero mean and variance $\sigma^2_{\epsilon,t}$. J is the total number of nodes in the system.

The use of 30 sequences is a tradeoff between computation time and the representativeness of the hydrological process. Previous studies (Tilmant et al., 2012) have shown that using between 30 and 50 hydrologic sequences gives similar results.

Chapter 4

Results and Discussion

The overall objective of this PhD project, as defined in the introduction, was to develop an innovative market-based institutional arrangement that includes both water allocation policies and benefit sharing mechanisms, with the aim to encourage cooperation in transboundary river basins. The arrangement efficiently allocates water resources, then applies a sharing rule to ensure the equitable re-allocation of the economic benefits of cooperation back to the water users. For the case study, a hydro-economic model was employed for water allocation and the sharing rule developed was based on bankruptcy theory.

In this chapter, the main findings of the three activities that make up this PhD project, based on methods presented in Chapter 2, are presented, and recommendations for future investigations are provided. For detailed results and discussions, specific to each activity, see **Papers I, II and III** (Appendix A).

4.1 Hydrologic and economic impacts of different management scenarios (Activity #1)

In **Activity #1** the hydrologic impacts and economic benefits of cooperation in the Eastern Nile River Basin are assessed. Various development scenarios (for example, increased consumptive water uses upstream) and management scenarios (including cooperative vs non-cooperative operation of a major upstream hydropower station) are analyzed. The 4 scenarios tested (S1-S4) are described in detail in Section 3.3 and shown in Figure 3.6. These scenarios are referred to as follows: S1 represents the current (baseline) infrastructure and irrigation schemes (Figure 3.6(a)); S2 is a future scenario in which the GERD is online, but irrigation areas are the same as in S1 (Figure 3.6(b)); S3 is the same as S2, but the GERD is operated to maximize hydropower revenues in Ethiopia only; S4 is a second future scenario in which the GERD is online and there is an increase in the existing irrigation areas in Sudan and Ethiopia to reflect plans for irrigation expansion in these two countries (Figure 3.6(c)). The integrated, stochastic hydro-economic model, described in Chapter 2, is used to carry out the assessment. In the following overview of the results, the allocation decisions that are determined by the hydro-economic model are shown, after which the resulting economic effects are presented.

4.1.1 Results

Allocation decisions

Reservoir storage levels The draw-down refill cycles for the GERD, for each scenario, are shown in Figure 4.1.

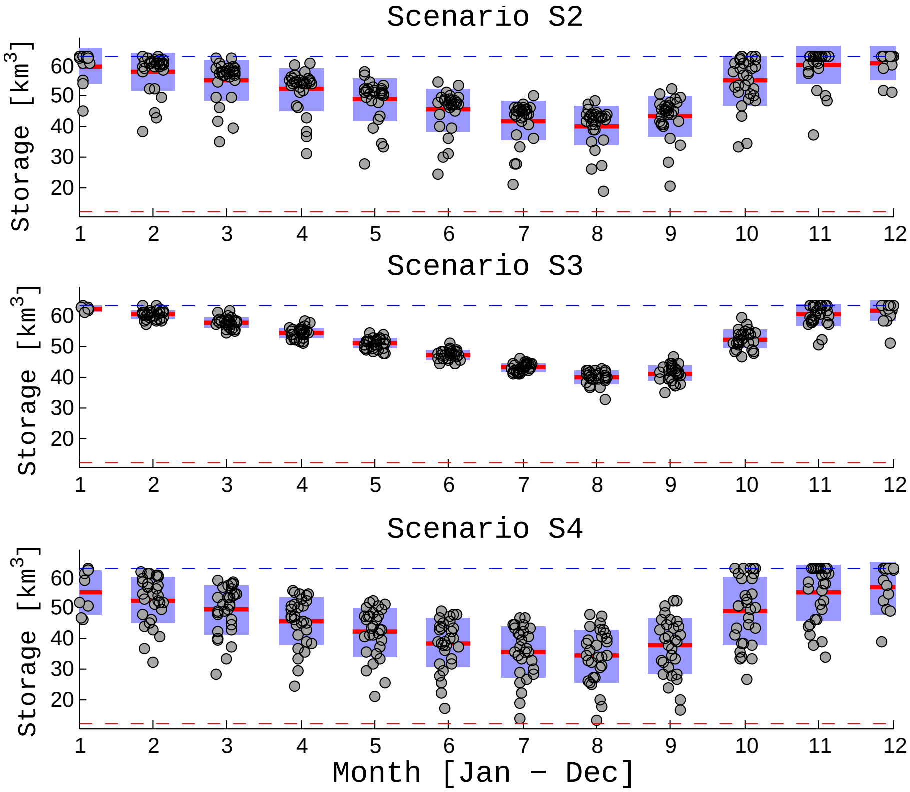


Figure 4.1: Draw-down refill cycles for the GERD. S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia. SDDP- derived storage volumes for each hydrologic sequence are shown as points, the height of the box corresponds to one standard deviation from the mean (i.e.: the 68% confidence interval assuming that the storage volumes are normally distributed) and the band near the middle of the box indicates the mean storage volume. The dashed lines at the top and bottom of each graph mark the high storage and low storage levels, respectively, in the reservoir.

The GERD, once online, is expected (on average) to exploit about one half of its storage capacity. This is a trade-off between keeping the pool elevation high for increased productivity of the power plant and emptying the reservoir to avoid excessive spillages losses. In S2 the GERD is operated in conjunction with the other infrastructure in the basin (mostly the Aswan High Dam (AHD)) and the storage levels tend to be more variable over the 30 hydrologic scenarios (as seen by the spread of the points at each month). This means that water held in storage at the GERD is being used to balance irregular flows downstream. When the GERD is operated to maximize the net benefits from hydropower generation in Ethiopia only (S3), the year-to-year variability of the storage levels at the GERD is nullified. The GERD is no longer being used to balance downstream flows, only to maximize hydropower output at this site. Finally, in S4, with increased upstream irrigation demand, a noticeable decrease in storage is observed. The levels are lower overall and the variability greatly increases. In fact, under very dry conditions, the reservoir may drain almost completely (down to the low storage level defined in the model).

The draw-down refill cycles for the AHD, for each scenario, are shown in Figure 4.2. Results show that in the current situation (S1), the year-to-year variability is significant, as there is no upstream infrastructure with multi-year storage capacity to regulate flow. When the GERD is online (S2), the AHD is operated at a higher and more constant level due to upstream regulation by the GERD. The unilateral management of the GERD (S3) results in pool elevations at the AHD being slightly higher than in the current scenario (S1) but lower than when the GERD is coordinated (S2). There is a greater variability in storage levels because the AHD must manage variations in flow levels as this is only partially accomplished by the GERD in this scenario. In (S4), we see the AHD is being operated at lower pool elevations with greater variability. With greater water abstractions upstream, the system is optimized to save water by reducing storage at the AHD, thereby reducing evaporation losses.

Evaporation losses Results from the analysis of evaporation losses in each country, under each management scenario studied, show that annual evaporation losses in Ethiopia, in all scenarios, are about 800 hm^3, which corresponds to about 1% of the annual flow of the Nile. This is a result of the lower temperatures and greater rainfall that characterize the headwater region of the Blue Nile. In Egypt, in all of the management scenarios, losses are much more significant, ranging from 11.5 km^3/yr to 12.3 km^3/yr. Higher evaporation values are observed when the GERD is online (S2) due to the AHD being operated at a higher level. The model calculates that the hydropower benefits that result from keeping a higher head on the turbines at the AHD outweigh the losses from evaporation due to these higher storage levels. The combined losses from Roseires, Sennar and Merowe, in Sudan, are around 2.3 km^3/yr. These losses remain fairly constant across all scenarios because, in contrast to Egypt and Ethiopia, the relatively low storage capacity in Sudan does not allow for major changes in the monthly operation of those reservoirs, resulting in little change in evaporation losses.

Cross-border flows Figure 4.3 shows the monthly outflow from the GERD. An analysis of the results reveal the hydrologic risk over the basin depending on the management scenario.

With the GERD online (S2, S3 and S4) (1) low flows are augmented to the extent that about 3 km^3/month are secured at least 90% of the time (F(X)=0.1), compared to only 35% of the

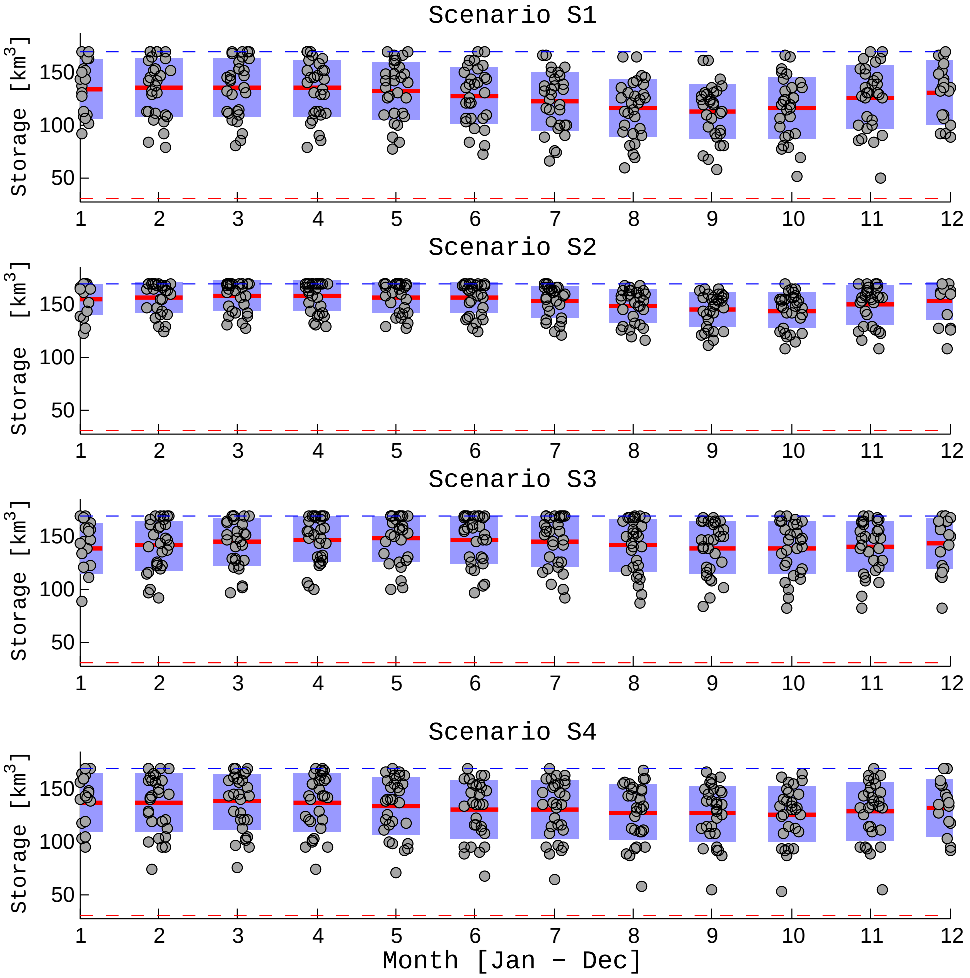


Figure 4.2: Drawdown-refill cycles for the AHD. S1=Baseline scenario; S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

time (F(X)=0.65) under natural conditions; (2) high flows are decreased, with the monthly outflow reduced by a factor of two, from about 8 km^3 to 4 km^3, at an exceedance probability of 10% (F(X)=0.9); and (3) the monthly cross border flows are constant 65 to 75% of the time ($0.1 < F(X) < 0.75$-0.85). A more constant water supply to Sudan and Egypt is ensured, due to flow regulation by the GERD, thereby reducing their hydrologic risk exposure to droughts and floods. This is especially important for Sudan due to the limited water storage capacity within the country, which is not the case for Egypt with the large storage capacity of the AHD.

Economic results

Hydropower generation The per country annual energy production in the Blue Nile/Nile are presented in Figure 4.4. Increases in energy production of 15% and 2% are shown in Sudan and Egypt, respectively, when the GERD is online (S2), as a result of reduced spillage

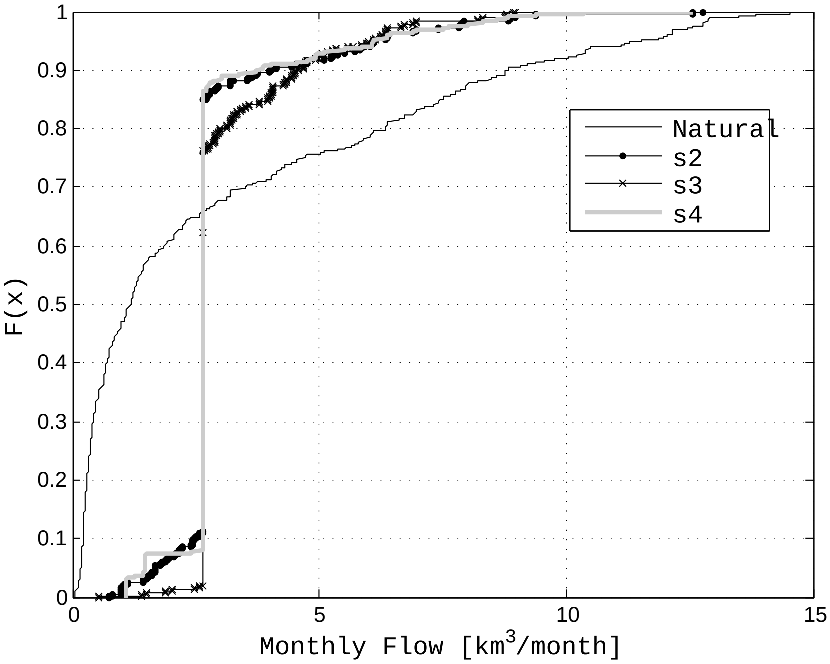


Figure 4.3: Monthly outflow from the GERD. S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia. This graph displays the statistical distribution of outflows from the reservoir. The empirical cumulative distribution function (CDF) gives the non-exceedance probability F(X) of any given outflow (X).

and higher pool elevations in the reservoirs located downstream of the GERD. The lack of coordination in reservoir operation (S3) yields a 4% reduction in power output from the Sudanese generators with negligible gains and losses in Ethiopia and in Egypt respectively. The impact of irrigation expansion (S4) falls, essentially, on Egypt (-3% of energy output) due to decreased storage levels at the AHD. Ethiopia is mostly unaffected because the increase in net irrigation consumptive uses around Lake Tana is not significant (<200 hm^3) compared to river flow at the GERD. Sudan is also mostly unaffected since storage capacity is limited in the country and reduced monthly discharges, due to upstream water withdrawals, implies lower spillage losses.

Short-run net benefits To better understand the exposure of downstream countries to the GERD, the statistical distributions of the combined net benefits in Sudan and Egypt are displayed in Figure 4.5. In the current situation (S1), the combined benefits range from 4.9 billion US$/yr to 6 billion US$/yr depending on whether the hydrologic conditions are dry or wet. When the GERD is online, minimum benefits in the downstream countries increase to about 5.6 billion US$/yr while the maximum remains unchanged. This indicates the positive role played by the GERD during dry years and its ability to increase water supply to these downstream countries under adverse hydrologic conditions. Even in average years (F(X)=0.5) we see a slight increase in the net benefits, compared to the current situation. Irrigation

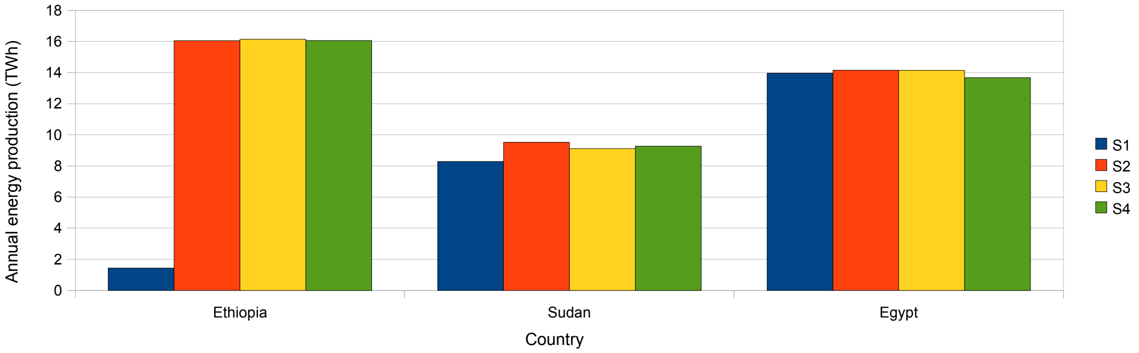


Figure 4.4: Per country annual energy production in the Eastern Nile River Basin. S1=Baseline scenario; S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

expansion in Sudan and Ethiopia (S4) yields an increase of about 180 million US$ which remains fairly constant throughout the hydrologic scenarios. In general, the total net benefits in Sudan and Egypt become more constant over all hydrologic scenarios when the GERD is online.

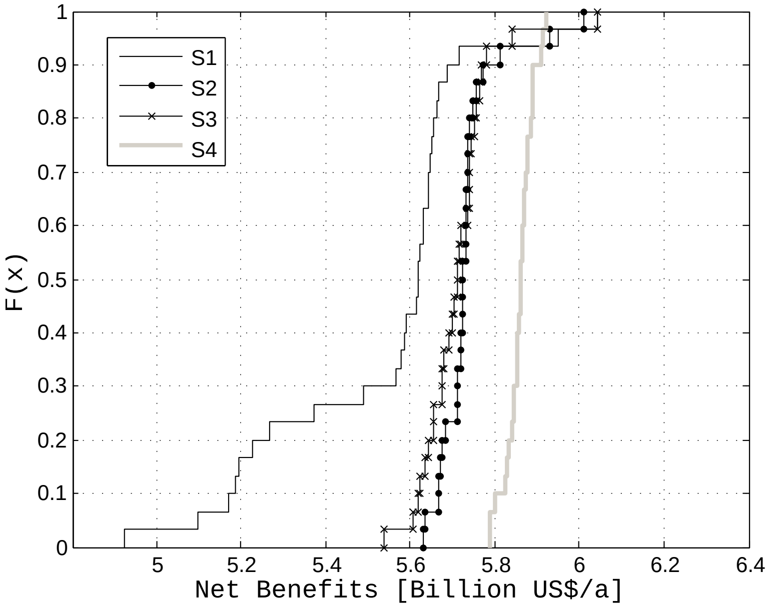


Figure 4.5: Net benefits in Sudan and Egypt. S1=Baseline scenario; S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

Figure 4.6 shows the horizontal difference between the statistical distributions of net benefits in the current situation (S1) and when the GERD is online (S2). This gives the statistical distribution of the externalities associated with the GERD on the agricultural and energy sectors in Sudan and Egypt. 90 million US$/yr in benefits is secured at least 90% of the time, 145 million US$/yr will be exceeded 30% of the time, and 500 million US$/yr will be ensured in at least one year out of ten.

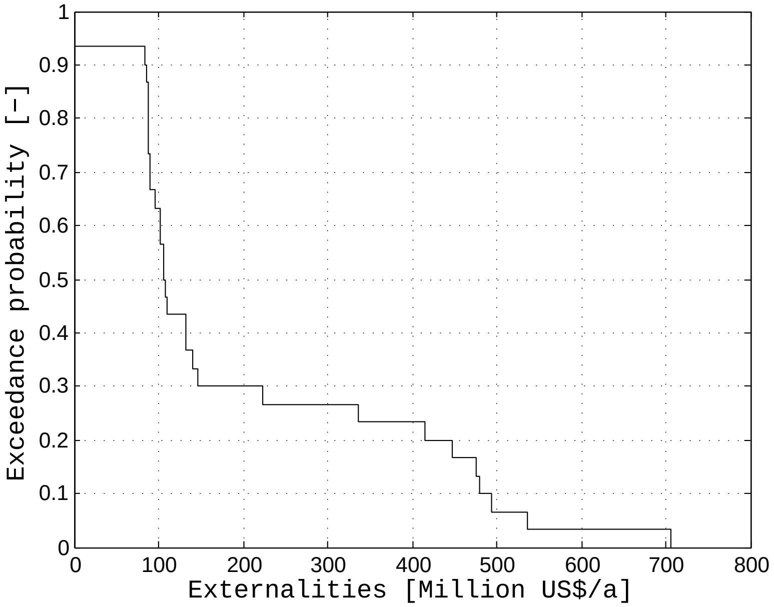


Figure 4.6: Externalities in Sudan and Egypt.

4.1.2 Discussion

In this study, the basin-wide allocation model uses SDDP, an algorithm that can solve large-scale stochastic optimization problems. The model determines economically efficient allocation policies, including reservoir releases, and then simulates the operation of the system for various hydrological scenarios. In this case study, 30 hydrological scenarios were used, in comparison to other studies (Kahil, Dinar and Albiac, 2016; Jeuland et al., 2014) that analyze 3 scenarios only (high flow, low flow, normal flow).

The results of applying SDDP to the Eastern Nile River Basin show that an agreement to cooperatively manage the basin, and its infrastructure, would significantly increase the basin-wide economic benefits, particularly in periods of low flow. As well, downstream Egypt and Sudan can expect to benefit from positive externalities, such as reduced floods and droughts, when the GERD will be online. One of the main benefits of the GERD lies is its ability to reduce hydrological uncertainty. Again, full cooperation is imperative in order for these benefits to be realized.

Tools such as SDDP enable the understanding of the effect of hydrologic uncertainty on management decisions and the determination of allocation policies that provide safeguards against hydrological risk. The benefits of cooperation, and the marginal values of water at various nodes in the system, can be calculated, and a picture of what water coordination would look like in a basin can be drawn.

With this information, institutional arrangements for sharing benefits in transboundary river basins can be designed, assuming cooperation to ensure that maximum basin-wide benefits are generated.

4.2 The institutional arrangement (Activity #2)

Based on the results obtained in **Activity #1**, an institutional arrangement was formulated which should encourage cooperation between riparian water users in transboundary river basins. In this arrangement, welfare in a river basin is distributed in an equitable manner after maximizing the economic benefits of water use using a method compatible with stakeholder involvement. The arrangement relies on: (i) water demand information (data) collected from the water users, (ii) scarce water resources are allocated in an economically efficient manner, to the water users, (iii) payments for bulk water use are collected from the users, and (iv) the total of these water payments is equitably redistributed back to the users, as monetary compensation, in an amount determined through the application of a sharing method that can, in principle, be developed through stakeholder input, thus based on a stakeholder vision of fairness. The whole system is overseen by a river basin authority (RBA).

The design of the arrangement is described in detail in Section 2.1 and shown in Figure 2.1.

To analyze this institutional arrangement, it is applied to a future water use scenario, again in the Eastern Nile River Basin.

4.2.1 Results

The efficient allocation of water, in Step 2 of the methodology, results in most water use agents receiving their unconstrained demand. The exceptions are agents I1, I4 and I14, who receive, on average, 1, 0 and 94% of their unconstrained demand, respectively (Figure 4.7). This result is not unexpected because, from an economic standpoint, irrigation in the Eastern Nile River Basin should take place downstream after water has been used for hydropower generation upstream (Whittington, Wu and Sadoff, 2005). As a result, these three irrigation agents have cooperation costs as well as, possibly, water costs, while all other agents only have water costs.

Overall, the agents with the smallest claims are all hydropower agents in Sudan (H9, H11, H14, H15) with marginal values that are almost equal to marginal values at the downstream sites (Figure 4.8). Note that this figure does not include the marginal values of water for the Atbara River and, therefore, H14 and H15 are not shown on the diagram. Agents H9, H11, H14 and H15 sell water downstream at about the same price that they paid for it, resulting in lower water costs. Figure 4.9 gives a basin-wide view of the percentage of the unconstrained benefits claimed by each agent, by agent type, on average. The irrigation agents upstream claim a larger percentage of their expected benefits because, first, they pay more for water

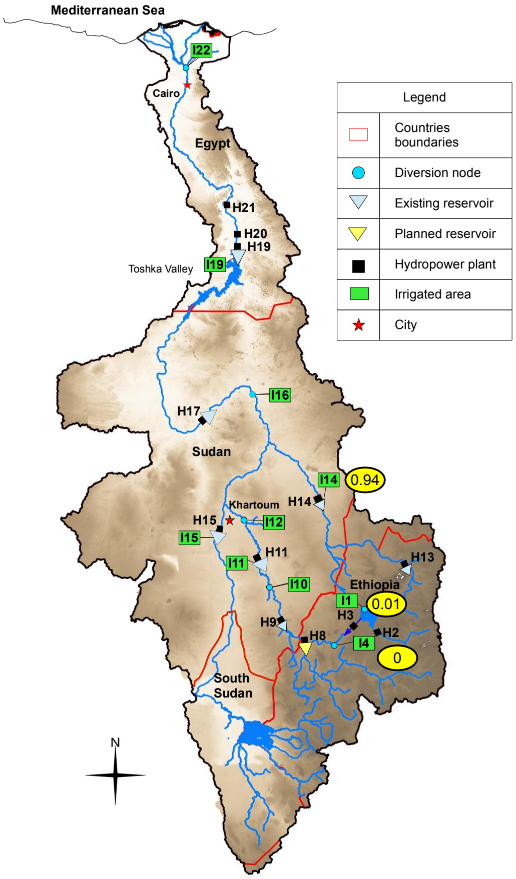


Figure 4.7: Average proportion of water allocation to unconstrained demand for all agents. Only the values for those agents in which the proportion is less than 1 are shown.

and, second, they also have cooperation costs. With respect to hydropower agents, H8 and H19 (Grand Renaissance and High Aswan, respectively) claim the largest percentage of their expected benefits. In both cases, the cost of water at these sites is much greater than the cost of water at the respective down-stream sites.

From the collection of bulk water charges (Step 3 in the methodology) an average of USD 3894 million is available to allocate between the agents. This does not include USD 3 million which is subtracted from the total estate to cover operating costs for the RBA. The total of the claims for all agents is calculated as USD 4266 million, on average, which means that there is a shortfall of USD 372 million between the amount available to share and the total claims of the agents, or about 9% of the total claims.

Using the bankruptcy rule developed for this activity, the transfer payment is calculated for each agent. The ratio of FNB to ENB, referred to as the initial ratio, and final net benefits plus transfer payments (FNB+tp) to ENB, referred to as the final ratio, are determined and analyzed. These results were analyzed over the 30 different hydrologic sequences to assess how

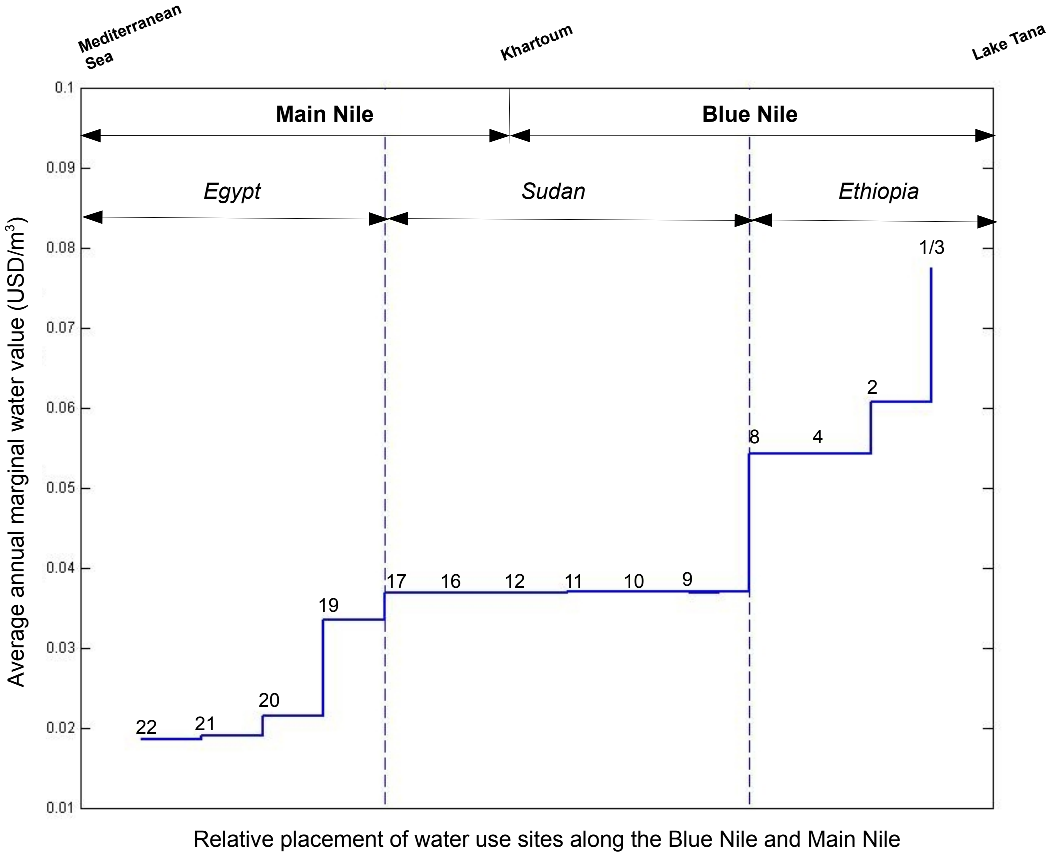


Figure 4.8: Marginal water values - Blue Nile and Main Nile.

this rule performs under varying hydrologic conditions.

Figure 4.10 shows the mean values for initial ratios (shown as large filled squares) and final ratios (shown as large filled diamonds) for irrigation agents as well as the values for each of the hydrologic sequences. Agents I1 and I4 receive little or no irrigation water, on average, as discussed previously. Agent I14 initially receives about 23% of its expected net benefits, on average. This agent is located at the Kashm El Girba dam, on the Tekeze-Atbara River. The flow of this river is highly seasonal, with annual flows entering Sudan from Ethiopia restricted to the flood period of July to October. The design storage capacity of the reservoir at this site is about 10% of the inflow; however, high sedimentation in the reservoir dropped the storage capacity by 50% as of 1977. This loss of storage capacity has resulted in severe water shortages during drought years and an associated decline in the crop area cultivated. As a result, the restriction of water for this irrigation agent is more probably due to the hydrology as opposed to being economic in nature. Due to flow variation, the marginal water values are highly variable at this site, resulting in a wide spread of initial ratios over the hydrologic sequences (as indicated by a large vertical spread of data points on Figure 4.10 for this agent). All other irrigation agents, as well as all hydropower agents, always receive their full unconstrained

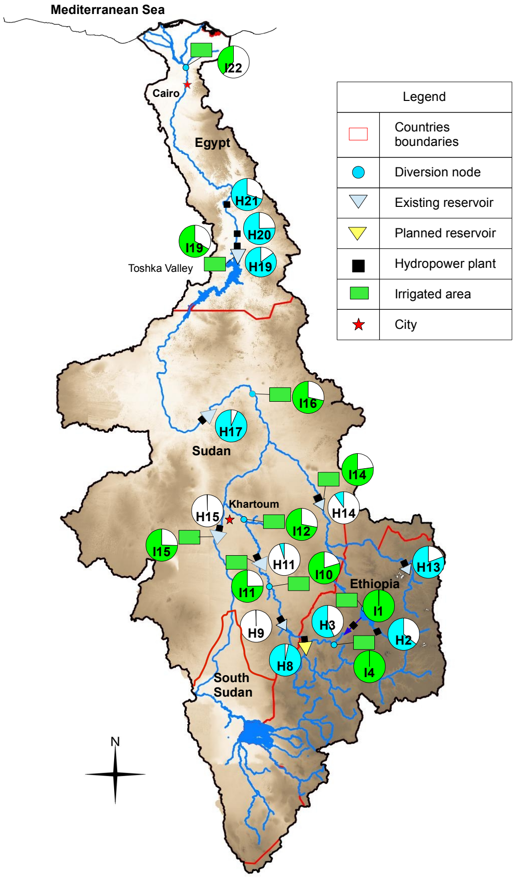


Figure 4.9: Percentage (average) of unconstrained benefits claimed by agents.

demand. Variability in the initial ratios of these agents is due to variability in the marginal water values over the hydrologic sequences.

Results for hydropower agents are shown in Figure 4.11. Here there is more variation in the initial ratio than for the irrigation agents. The upstream hydropower agents (H2, H3), and those on the Tekeze-Atbara River (H13, H14), have large variations in initial ratios as a result of large inter- as well as intra-year variations in flow (and subsequently in marginal water values), which occurs because these sites are all upstream of hydropower infrastructure. The agents with the smallest claims are the four smallest hydropower agents in Sudan (H9, H11, H14, H15). These agents have the largest initial ratios and, therefore, often do not receive monetary transfers. This also results in the final ratios for hydropower agents not being equal because the property of non-negativity, which is used to define the sharing rule, allows an agent to keep its initial benefits from water use even if this results in its final ratio being larger than those of the other agents.

Overall, the average final ratios for all agents (irrigation and hydropower) are equal, with the exception of agents H9, H11, H14 and H15, as mentioned above. There is also very little

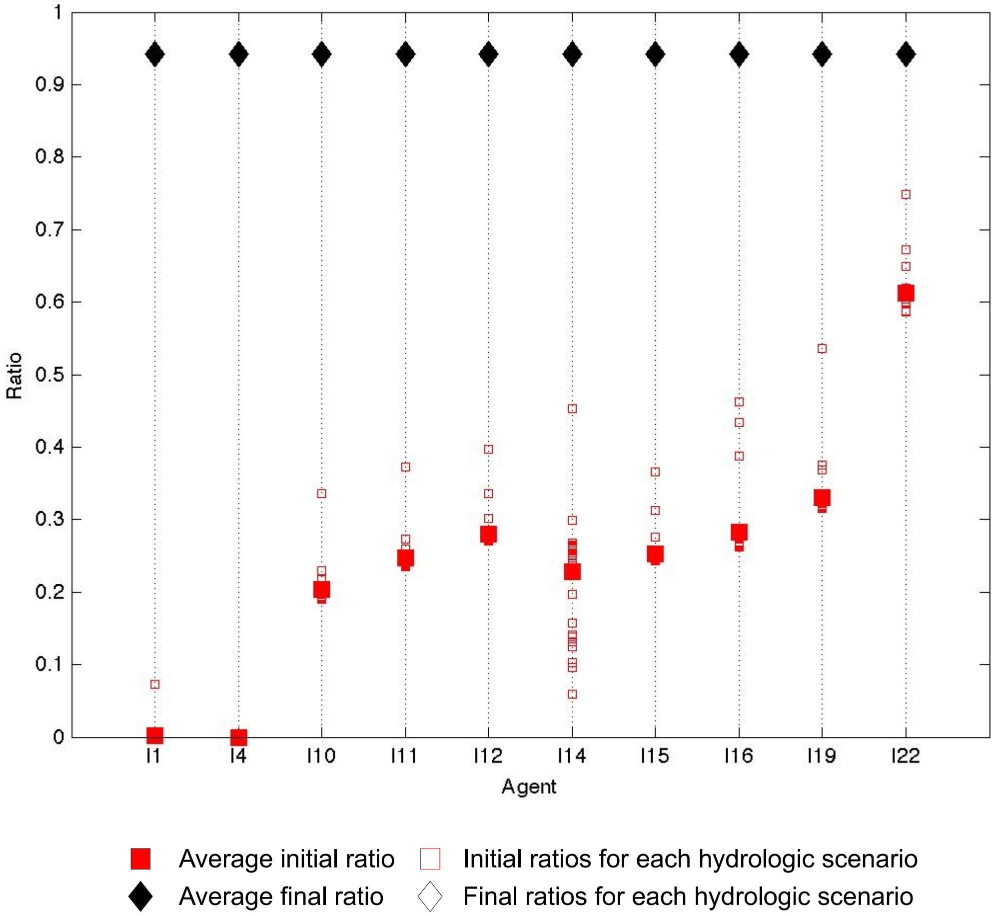


Figure 4.10: Initial and final ratios for irrigation agents.

variation in final ratio values with respect to hydrologic sequence. The final ratios for all agents vary from 93.5 to 95% of their uncontested benefits. This occurs because the initial ratios of the agents vary with the inter- and intra-annual variations in the marginal value of water. However, the cost of water also varies proportionally. As a result, the total claims of the agents, proportional to the amount available to share, does not vary significantly.

4.2.2 Discussion

In the determination of the efficient allocation policies, the results obtained in this activity are based on simple assumptions about irrigation and hydropower values in the case study. These are assumptions that have been made by other researchers (Whittington, Wu and Sadoff, 2005) and are generally consistent with international experience in well-run irrigation schemes and power systems. However, it is obvious that the quality of the results are dependent on the quality and availability of data to run the model, and on the assumptions made. It is assumed that, in the future, it will be realistic to get good quality data. Currently, market prices, either

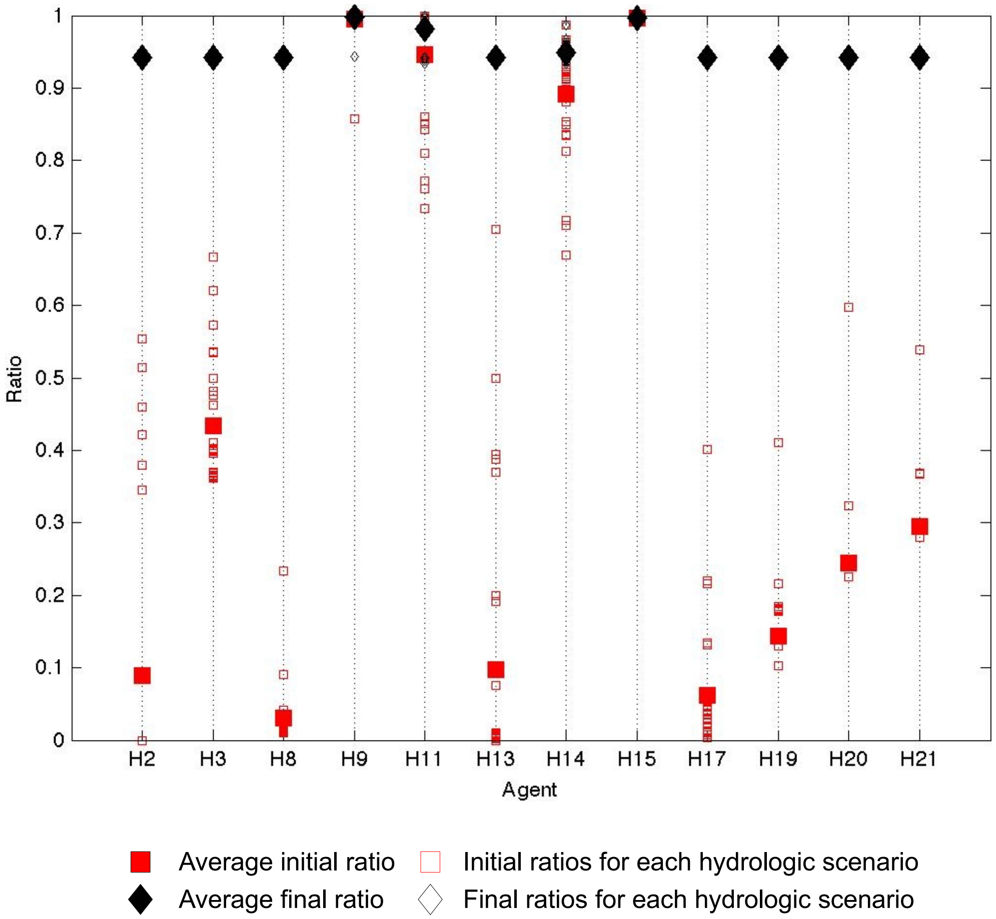


Figure 4.11: Initial and final ratios for hydropower agents.

national or international, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. This activity describes a system in which it is assumed that there is cooperation over the whole basin. This means that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. It is up to the RBA to check that the information is reliable. Increasingly, river basins are being monitored and the information required is becoming available. The system may not seem realistic at this point but, in the long-term, exchange of information will increase the availability of data over river basins. This increase in information exchange is in keeping with the obligation to cooperate and exchange information that is outlined in the UNWC.

The results that warrant a closer look are those for the upstream irrigation agents I1 and I4. It can be concluded that, in this case study, given the economic information used in the model, it is economically inefficient to irrigate upstream in the basin regardless of the hydrologic sequence (meaning that even in situations of high flow years, there is no irrigation water allocated to these agents). However, these two irrigation agents consistently demand fairly substantial transfer payments even though they do not contribute economically to the basin. This becomes an obvious problem of fairness for the other agents. If these results persist over a number of years, the RBA could use this information for better management by ensuring that agriculture is developed downstream or that upstream agricultural sites have a high productivity value. However, it should be noted that these irrigation schemes are rationed because the productivity of water that is used over the entire basin (0.05 USD/m3) is less that the marginal value of water at these nodes in the system. This productivity value is used because there is currently a lack of data for irrigation in the basin. The availability of economic/agricultural data in each irrigation scheme over the basin, as well as details on cropping patterns in each scheme, would allow the development a non-horizontal demand curve. If this were the case, high value crops in the upstream schemes may be irrigated and low value crops in downstream schemes may not be irrigated. This means that the irrigation water users that are rationed may change and may be spread out over the basin.

In analyzing the water allocation policies determined for this case study, there is no attempt to compare the results with current water use in the basin. The presented case study is hypothetical and is not consistent with the actual, current infrastructure or irrigation situation in the river basin. As well, an important aspect of the institutional arrangement is that the property rights of the riparian countries, that currently drive water allocation, are disregarded, as discussed in the methodology.

The results of this activity also demonstrate that the equitable sharing of economic benefits can be achieved through the use of analytical methods, such as those based on bankruptcy theory, which are flexible and can be modified to acknowledge the differences in the notion of equity between river basins. There are a number of ways in which benefits can be shared, and the results are based on the properties of equity that underlie each rule. There is no one way of sharing benefits in all river basins and commonly used methods may need to be adjusted before they can be applied to a particular situation. In this case study, even though the applied methodology results in a bankruptcy problem the fact that the final benefits of the users include the benefits of water use, as well as the transfer payment, requires that a new rule be developed. The advantage of the new rule is that it is based on the definition of equity chosen for this analysis, rather than using an existing rule in which stakeholders must agree on the equity requirement underlying the rule.

4.3 Bankruptcy methods for equitable sharing of benefits (Activity #3)

Activity #3 tests the results of three popular bankruptcy sharing rules to see how they perform compared to the rule developed in **Activity #2** to determine the monetary compensation to water users, and to illustrate how the results are different depending on the rule and the definition of equity that underlies the rule.

4.3.1 Results

The results of applying three common bankruptcy based sharing rules (PRO, CEA, CEL), each having a different definition of equity, are compared to the results obtained in the application of the ECO sharing rule in **Activity #2** on the basis of the proportion of the expected net benefits (ENB) that water users pay toward the cost of cooperation. This basis of comparison was chosen because the goal of the new ECO sharing rule is to allocate the total benefit to the agents to ensure "solidarity" in the basin, defined as the cost of cooperation being equally borne by all agents.

The equity considerations of each of the rules are as follows:

- CEA: all agents should have equal rights to the estate;
- CEL: all agents share, equally, the losses resulting from the estate being smaller than the total of claims to the estate;
- PRO: each agent should receive an equal proportion of their claims;
- ECO: each agent should pay the same proportion of their expected net benefits as cooperation costs.

Results for the application of the CEA rule are shown in Figures 4.12 and 4.13 for hydropower water users and irrigators, respectively. These figures show the cost of cooperation paid by each water use agent, as a percentage of their ENB. Large filled squares are the mean cost and the small unfilled squares show the costs for each of the 30 hydrological sequences analyzed. A high value for cost means that the agent is paying a greater percentage of its ENB as cost of cooperation. The CEA rule favours the agents with the lowest claims (Figure 4.14). All agents are compensated for 100% of their claims with the exception of agents H8 and I22 who have the highest claim amounts. As a result, these two agents bear the burden of paying for the cost of cooperation between the two of them. Agent H8 is shown to have a wider variability in cost over the 30 hydrological scenarios, compared to agent I22. By definition of the rule, the cost is dependent only on the claim of the agent. In the case of I22, the claim depends on the marginal value of water at the site, since the agent receives 100% of their water demand in all scenarios. The claim for H8, on the other hand, depends not only on the marginal water value at this node, but on the value at the downstream node, both of which vary depending on the scenario. As well, the water allocation to the hydropower nodes also varies from one scenario to another.

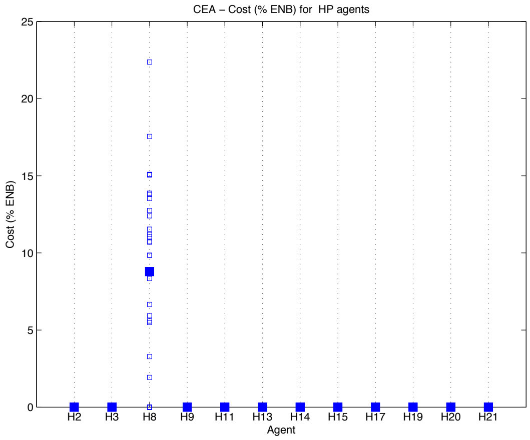


Figure 4.12: % of ENB paid as cost of co-operation by HP users as determined by the CEA sharing rule.

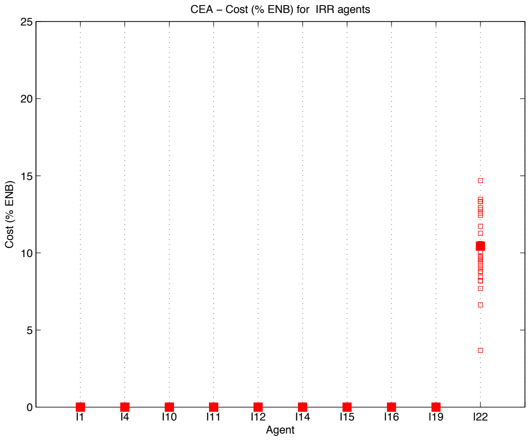


Figure 4.13: % of ENB paid as cost of co-operation by IRR users as determined by the CEA sharing rule.

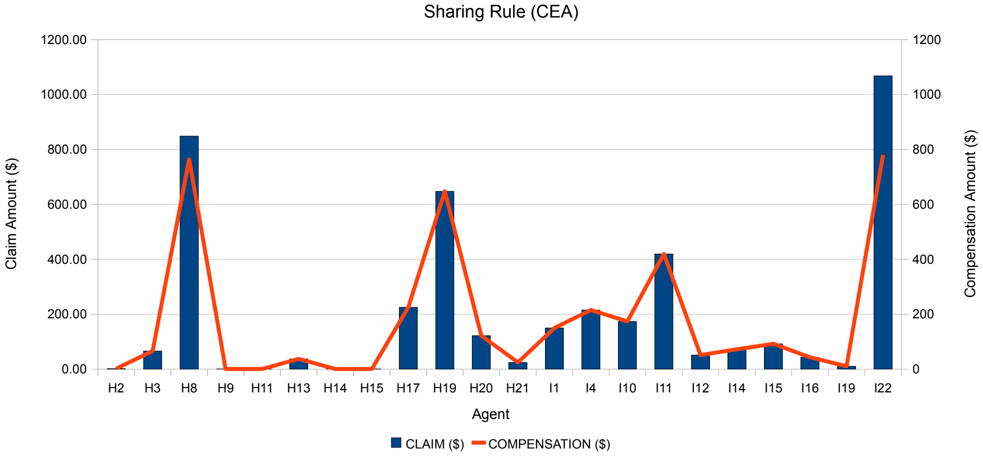


Figure 4.14: Claim Amount ($) vs. Compensation Amount ($) for CEA sharing rule.

Results for the application of the CEL rule are shown in Figure 4.15 for hydropower agents and Figure 4.16 for irrigation agents. The CEL rule favours the agents with the highest claims. The agents with the lowest claims do not necessarily have the highest initial ratios, which is a measure of the percentage of the expected benefits that are fulfilled through the use of water allocated to the agent ($\text{FNB}_j/\text{ENB}_j$). This can be observed in Figure 4.17. Using the CEL sharing rule, these agents ,then, pay a higher cost of cooperation. For example, H2 pays the highest percentage of costs, on average. This agent has a low claim amount and receives no compensation using the CEL rule, but only gets 8.9% of its benefits from water use, as shown in Figures 4.17 and 4.18. Compare this to agent H9 who also has a low claim amount and no compensation but gets almost 100% of its benefits from water use and pays very little in cooperation costs. This is a result of the cost that each agent must pay for water. Returning to Figure 4.8, agent H2 pays the difference between the marginal value of water at site 2 and site

8. Agent H9, on the other hand, pays the difference in marginal value of water between site 9 and site 10. The cost of water for H2, then, is much greater than that for H9. As a result, agent H9 pays very little in costs and receives almost 100% of the benefits from water use while agent H2 pays a large percentage of its benefits from water use as water costs. The agents favoured with this sharing rule are H8, H9, I11 and I22, who are always fully compensated, regardless of the hydrological scenario, because they always have the highest claims. Figures 4.15 and 4.16 show that all of the other agents have different degrees of variability in cost allocation over the 30 scenarios. Again, the hydropower users show more variability for the reasons explained above for the CEA rule.

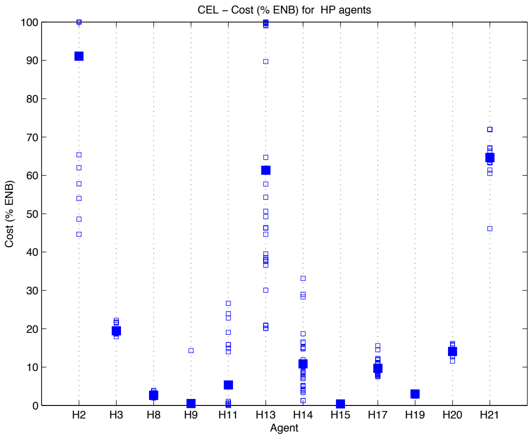


Figure 4.15: % of ENB paid as cost of co-operation by HP users as determined by the CEL sharing rule.

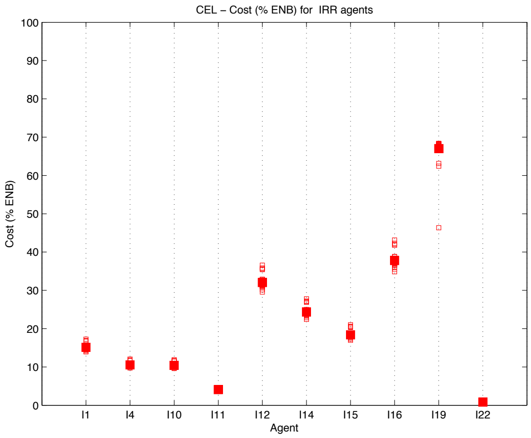


Figure 4.16: % of ENB paid as cost of co-operation by IRR users as determined by the CEL sharing rule.

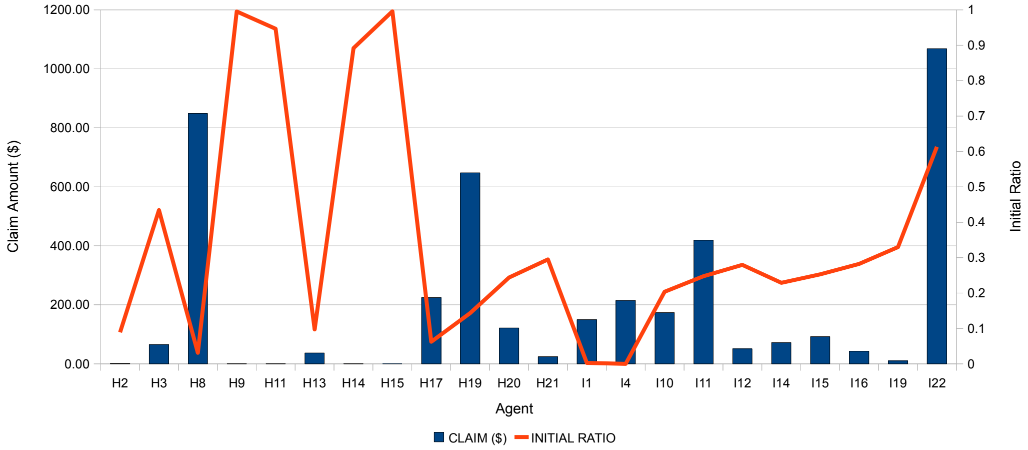


Figure 4.17: Initial Ratio vs. Claim Amount ($).

Although all agents receive the same proportion of their claims using the PRO sharing method (Figure 4.19), this rule favours those agents who have a large initial ratio to begin with. For example, I1, I4 and H8 have the lowest initial ratios (Figure 4.17) but pay the highest

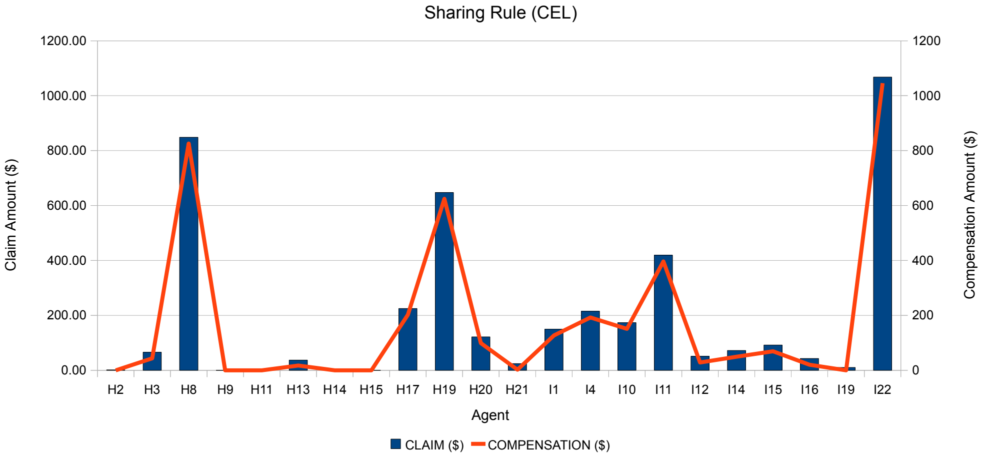


Figure 4.18: Claim Amount ($) vs. Compensation Amount ($) for CEL sharing rule.

percentage of benefits as costs. The costs, using this sharing rule, are also variable for all agents over the 30 hydrological scenarios, because the compensation is proportional to the claims and the claims vary over the sequences (Figures 4.20 and 4.21). Because, once again, this rule is based on the claims of the agent only, the hydropower agents experience a greater spread of cost over the hydrological scenarios. On average, however, the variability is relatively low with the difference between the low cost scenario and high costs scenario measuring about 3% of the ENB.

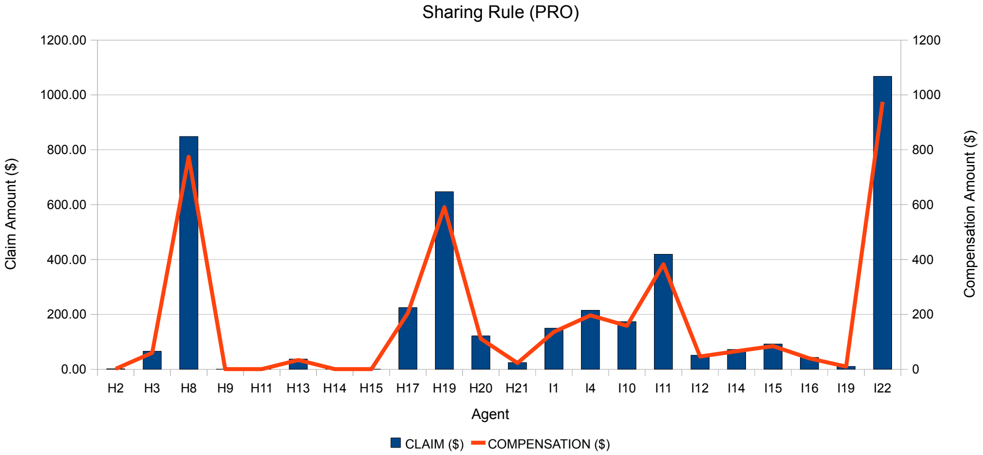


Figure 4.19: Claim Amount ($) vs. Compensation Amount ($) for PRO sharing rule.

Using the newly developed sharing rule (ECO), agents receive varying proportions of their claims to ensure that they all finally pay the same costs of cooperation, as a proportion of their ENB (Figures 4.22 and 4.23. As seen in Figure 4.22, agents H9, H11, H14 and H15 actually have lower cooperation costs, on average. This results from the property that no agent gets a negative amount of compensation. These agents have initial ratios higher than

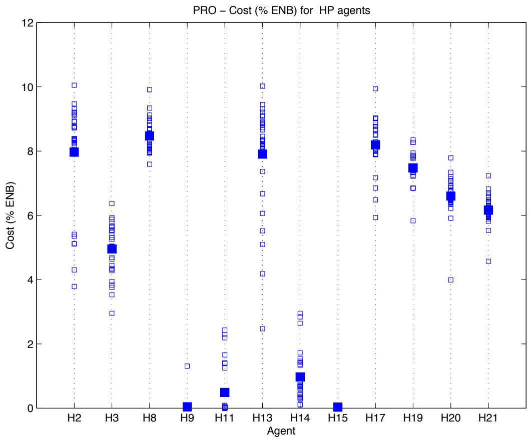


Figure 4.20: % of ENB paid as cost of co-operation by HP users as determined by the PRO sharing rule.

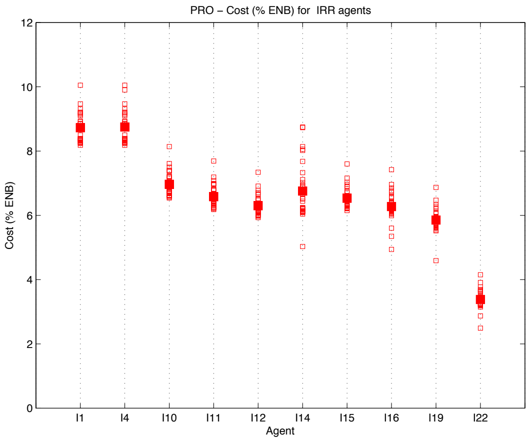


Figure 4.21: % of ENB paid as cost of co-operation by IRR users as determined by the PRO sharing rule.

the final ratio ($(\mathrm{FNB}_j + \mathrm{b}_j)/\mathrm{ENB}_j$) obtained for all agents after sharing the estate. As a result, although they do not get any compensation, their final costs are lower than those of the other agents. Again, these are the agents that pay the least for water because the marginal water values at the site of water abstraction and downstream are similar (Figure 4.8). The variability of costs over the 30 hydrological sequences is similar for all agents, regardless of the sector to which they belong. Because the calculations are based on the initial and final ratios, and not the actual claim amount, this nullifies the effect of the variability in the difference between water allocation and water demand. In actuality, the range of variability is low (around 2% of the ENB depending on the hydrologic scenario). Only H14 has high variability because this agent receives very little in compensation.

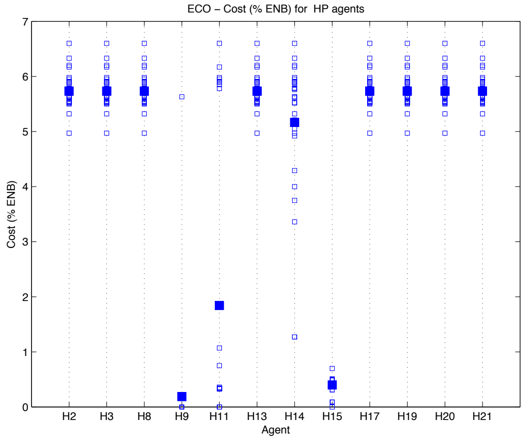


Figure 4.22: % of ENB paid as cost of co-operation by HP users as determined by the ECO sharing rule.

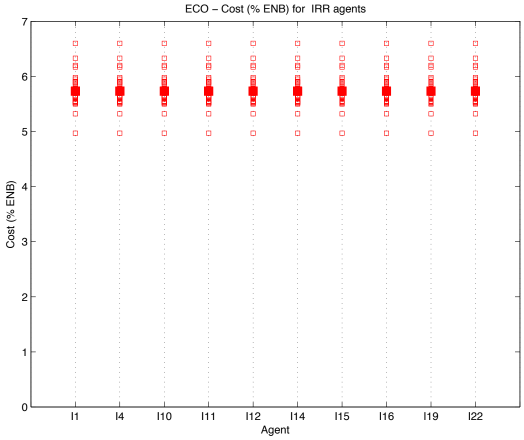


Figure 4.23: % of ENB paid as cost of co-operation by IRR users as determined by the ECO sharing rule.

CEA and CEL are egalitarian sharing rules. The equity consideration of these rules is that all agents should have equal rights to the estate (either as benefits or losses). For the PRO sharing rule, there is inequality in the amounts received by each agent, however, priority of one agent over another is ruled out because they all receive the same percentage of their claim. As well, proportional rules, in general, spread the shortages over all agents. In all of these sharing rules, the property of "equal treatment of equals" applies, meaning that agents with equal claims will receive the same amounts of benefits, regardless of the benefits received from water use.

In comparison to the common bankruptcy rules, the rule proposed in **Activity #2** distributes the estate by taking into account the benefits already received through water allocation, measured as the initial ratio of an agent. Based on this approach, agents with smaller initial ratios are entitled to a higher percentage of compensation based on their claim. Note that the property of "equal treatment for equals" does not apply in this sharing rule.

4.3.2 Discussion

The main observation from the results of this activity is that all rules are equitable in the sharing of benefits, based on the properties that define fairness for each rule, as long as there is agreement among the stakeholders. In this activity, the ECO rule defines equity as the sharing of cooperation costs in equal proportion to the ENB of water users in the basin. The other rules each define equity in different ways. Equity considerations are more than likely different for each river basin. In acknowledging these differences, there is a need to define sharing rules that apply properties specific to each basin. Bankruptcy methods show promise as useful tools to solve these types of problems.

Although bankruptcy theory is only one method which can be applied to share benefits, an advantage of using a rule based on bankruptcy theory, compared to other types of sharing methodologies (for example, game theory), is the relative simplicity of the concept. A rule would need to be easily understood to be accepted by negotiating parties. In fact, it has been mentioned that the value of game theory might be unclear to the water resources community as a result of the lack of understanding of the basic concepts (Madani, 2010). A lack of understanding of the concepts behind the sharing of the benefits can lead to misuse of the rules or to distrust in the results. Another advantage is that the three common rules analyzed in this activity define proportional sharing (PRO) and equal sharing (CEA, CEL) which are simple techniques often used to solve disputes in water management (Oftadeh, Shourian and Saghafian, 2016; Garrick, 2015).

4.4 Recommendations for future investigations

The results of this research may be considered as a foundation for future work in this subject area. The following specific recommendations are made regarding future research to expand this work:

- **Consideration of additional water use sectors in the Eastern Nile River Basin.** This research focussed on the two main water uses in the Eastern Nile River Basin case study: irrigation and hydropower generation. This particular case study should be expanded to include other important water uses such as environmental flows and municipal water use. As well, currently planned irrigation and hydropower infrastructure should be taken into account to indicate how the results of the methodology would change as a result of increased infrastructure in the basin.
- **Analysis of other case studies.** The application of the proposed methodology to other river basins would allow an analysis of how it would function in different river basin configurations and characteristics.
- **Stochasticity of water flow.** This activity touched on a stochastic analysis of the results, with respect to flow variation. The described methodology should also be analyzed to determine how it would function under various climate change scenarios. In the current study, a historical record of incremental inflows is used to estimate the parameters of the build-in multi-site periodic autoregressive hydrological model. The assumption that historical weather patterns are representative of possible future conditions is made. In other words, we assume that the climate is stationary. However, climate change is expected to affect hydrology, and the availability of freshwater resources, making this assumption questionable. To address this issue, new hydrology corresponding to different climate change scenarios, should be generated, and new time series of river discharges could then be processed by SDDP. Hydro-climatic changes will likely also affect water demands (e.g. Crop evapotranspiration) and hence the way water users will bid. This could also be addressed by running scenarios of water demands. Also, the question of whether different sharing rules should be applied depending on flow scenario (high flow years, low flow years) should also be assessed. This would involve the definition of sharing rules, given different climatic conditions, and how the rule might change under these conditions. Again, these rules will need to be defined with stakeholder input.
- **Analysis of equity in different river basins and how rules can be developed.** An analysis of equity considerations in different river basins would strengthen the understanding of the use of available analytic methods to develop sharing rules.
- **Inclusion of the principle of sustainability into the methodology.** Sustainability and equity may be the two most important principles of water allocation. In this

research, the focus was on the equitable sharing of water. How the principle of sustainability can be incorporated into the methodology also needs to be addressed. As mentioned previously, intergenerational equity and ecological services provided by water need to be considered and optimized. One important aspect that needs to be considered is the determination of the in situ value of the water resources and how this can be modeled in water allocation decisions.

Conclusion

An institutional arrangement for welfare distribution in transboundary river basins should answer the following fundamental questions: (i) how can the benefits of water use be quantified and monetized, ii) what mechanism can be used to allocate benefits, and (iii) upon what criteria should the sharing of benefits be based to ensure efficiency and equitability. There is no unique response to these questions. In this PhD project, one approach for distributing the benefits of cooperative management in a river basin system, comprised of rival and non-rival water uses, is proposed. To illustrate the approach, the Eastern Nile River Basin was used as a case study, due to the important hydropower and agricultural sectors spread over the three riparian countries as well as to the history of non-cooperation in the basin.

The designed methodology is based on the welfare distribution for each agent being equal to the sum of its benefits from water use plus a monetary transfer. First, efficient water allocation is implemented in order to maximize the benefits in the river basin. Second, a charge for the use of water is established. The price that agents pay for the use of water is equal to the marginal value of water at the site at which the agent receives its allocation. The total of the water charges is equivalent to the overall value of water in the basin that is used in the sectors being studied. Finally, the total of the water charges are equitably reallocated over the basin using a sharing method based on a stakeholder perception of fairness. The existence of an RBA, and cooperation between water users, is assumed and the river basin is operated as an auction-based water market with the advantages of resource use optimization, improved resource reliability and enhanced security of resource supply.

This methodology can be useful for policy-makers in transboundary river basins because the solution is more likely to be perceived as equitable, resulting in water use agents being more open to cooperation. The methodology is flexible in that there is no set way to allocate the water over the basin. Any hydro-economic model (or another method) can be used as long as the amount of water allocated to each agent, as well as the marginal value of water for each agent, is available. The interest in using hydro-economic models is that they provide a means of evaluating the efficient use of water and also provide a basin-scale view of the effects of water management practices on the economic benefits that can be generated in a basin.

The development of the sharing rule is based on stakeholder input and will depend on specific conditions in specific river basins. Bankruptcy rules were analyzed for use in sharing benefits in the case study. Axioms are imposed, based on a stakeholder vision of fairness, and a unique solution for the distribution of monetary payments is derived. This technique may lead to a sharing solution that is more acceptable to shareholders because the definition of the sharing rule is not in question, as would be the case if existing bankruptcy rules or other game theory solutions, with their inherent definitions of fairness, were applied.

This PhD project highlights the challenges in achieving trade-offs between the water allocation principles of efficiency and equity and suggests that by coupling these and considering efficiency as an important and necessary, but ancillary, tool to equity, cooperation between riparian water users in transboundary river basins can be encouraged, leading to improved management of scarce water resources.

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Appendix A

Papers

I

Hydro-economic Risk Assessment in the Eastern Nile River Basin

Diane Arjoon, Yasir Mohamed, Quentin Goor
and Amaury Tilmant

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En 2011, le gouvernement éthiopien annonçait son intention de construire le Grand Ethiopian Renaissance Dam (GERD) sur le Nil Bleu, à l'est de sa frontière avec le Soudan, pour un coût atteignant près de 5 milliards de dollars. Le projet devrait générer plus de 5 Twh d'électricité par année et comprendra un réservoir d'une capacité supérieur à 60 km3. Ce projet fait partie d'un plan plus vaste du gouvernement éthiopien pour augmenter sa capacité hydroélectrique. Cependant, ce plan fait face à des préoccupations provenant principalement du gouvernement égyptien, lequel dépend fortement du débit du Nil originant d'éthiopie. Le gouvernement éthiopien soutient que le barrage fournira de l'électricité pour les éthiopiens et les pays voisins, tout en réduisant les inondations en aval par des débits plus constants et prévisibles. Cette étude fournit une analyse indépendante des risques hydrologiques et économiques rencontrés par les pays situés en aval lorsque le GERD sera en opération. Pour ce faire, un modèle intégré stochastique hydro-économique de l'ensemble du bassin Oriental du Nil est utilisé pour analyser différents scénarios de développement et de gestion. Les résultats indiquent que si les pays riverains conviennent d'une gestion commune du bassin, incluant ses infrastructures majeures, le GERD augmenterait significativement les bénéfices pour le bassin, en particulier en éthiopie et au Soudan, et générerait des effets positifs au Soudan et en Egypte pendant les années sèches.

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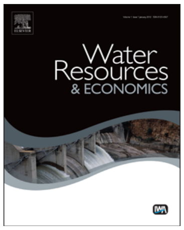

Hydro-economic risk assessment in the eastern Nile River basin

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ABSTRACT

In 2011, the Ethiopian government announced plans for the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile, east of its border with Sudan, at a cost of almost 5 billion USD. The project is expected to generate over 5 TWh of electricity per year and will include a reservoir of more than 60 km^3 capacity. This project is part of a larger development scheme, by the Ethiopian government to expand its hydropower capacity; however, the scheme faces strong concerns, mainly from Egypt who are highly dependent on Nile River flows originating in Ethiopia. The Ethiopian government argues that the dam would supply electricity for Ethiopians and neighbouring countries and would generate positive externalities downstream by reducing floods and providing more constant and predictable flows. This study provides an independent analysis of the hydrologic and economic risks faced by downstream countries when the GERD will be online. To achieve this, an integrated, stochastic hydro-economic model of the entire Eastern Nile River basin is used to analyse various development and management scenarios. Results indicate that if riparian countries agree to cooperative management of the basin, and its major infrastructure, the GERD would significantly increase basin-wide benefits, especially in Ethiopia and in Sudan, and would generate positive externalities in Sudan and Egypt during dry years.

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1. Introduction

The Blue Nile River is shared between Ethiopia and Sudan and is an extremely important resource for Egypt as it is the main source of water flowing into the Main Nile River. No formal mechanisms to cooperatively develop and manage the river are currently in place, although the three riparian countries have agreed to collaborate, in principal, through the Nile Basin Initiative (NBI) [1]. Significant potential benefits of cooperation exist; however, all three countries continue to develop unilateral projects to harness the potential of the river [2].

In 2011, the Ethiopian government announced plans for the construction of the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile, east of its border with Sudan, at a cost of almost 5 billion USD. The project is expected to generate over 5 TWh of electricity per year and will include a reservoir of more than 60 km^3 in capacity. This project is part of a larger development scheme, by the government, to expand its hydropower capacity.

Ethiopia has abundant water resources and massive hydropower potential but, as of 2001, only 3% of this hydropower potential had been developed [3]. As well, only 5% of the irrigable land in the Blue Nile basin had been developed for food production [4] while only 17% of the population had access to electricity, with 94% relying on fuel wood for cooking and heating [5]. The Ethiopian government argues that the GERD will supply electricity for the country as well as generate surplus cheap energy for export to neighbouring countries. It has been suggested that a strong link exists between energy and development, and that access to electricity, including access in rural areas, is one of the keys to reducing poverty [6]. It is also expected that the huge reservoir would generate positive externalities downstream by reducing flooding and sediment loads and by providing more constant and predictable flows.

Since the announcement of the project, Egypt, primarily, has expressed its concern. Egypt's main argument against the project is that other Nile basin countries have alternative water sources, but the Nile is the only source of water in Egypt. Egypt insists that its historic rights to the water of the Nile (rights of 55.5 billion m^3 per year from the 1959 bilateral agreement between Egypt and Sudan), be respected, and there is a concern that the GERD will decrease the amount of water that Egypt will ultimately receive.

Prior to the GERD, Ethiopia had plans to build four dams on the Ethiopian stretch of the Blue Nile: Karadobi, Beko-Abo, Mandaya and Border (which has been replaced by the GERD). A number of studies have been carried out on the hydrologic and economic effect of these dams on the downstream riparians. Both Goor et al. [9] and McCartney et al. [11] find that the installation of these four dams would result in peak flows in the Blue Nile being decreased while low flows are augmented, reducing the risk of floods and droughts. Whittington et al. [7] show an increase in benefits of between 2.76 billion USD and 3.63 billion USD with full Blue Nile basin development (all proposed dams in Ethiopia are built). This increase is mainly due to the economic benefits from additional hydropower production and to savings from storing water upstream in Ethiopia rather than downstream in Egypt. Jeuland and Whittington [25] look at a real options approach to planning the new infrastructures in Ethiopia and conclude that the results provide strong support for the decision to move forward with the construction of an initial dam in the Blue Nile cascade. Dinar and Nigatu [26] examine water trade as a means to enable cooperation among Blue Nile countries sharing the resource, and study the distribution of the additional gains due to cooperation using game theory.

In this study, we assess the hydrologic and economic risks faced by the hydropower and agricultural sectors in Sudan and Egypt when the GERD will be online. A basin-wide, integrated hydro-economic model has been developed which links hydrologic, economic and institutional components of the river basin to identify optimal allocation decisions in order to maximise the aggregated basin-wide net benefits. This model is solved using stochastic dual dynamic programming (SDDP) which has been successfully employed to solve multipurpose, multi-reservoir operation problems with stochastic inflows. Tilmant et al. [22] used SDDP to determine the economic value of storage in the Euphrates River basin, Tilmant and Kinzelbach [23] looked at the cost of non-cooperation in the Zambezi River basin and Marques and Tilmant [24] assessed the economic value of coordination in large-scale multireservoir systems in the Parana River.

Unlike most hydro-economic models used in previous studies, which are deterministic, a stochastic programming formulation allows us to understand the effect of hydrologic uncertainty on allocation policies and to include the notion of risk in our analysis by providing values on, and statistical distributions of, positive and negative externalities, which was often ignored in previous studies [7].

This paper begins with a presentation of the study area, followed by a detailed description of the hydro-economic model used in the study and the scenarios that were modelled. Results are then presented and discussed. Our analysis concludes with a look at model limitations and future research needs.

2. Materials and methods

2.1. Study area

The Blue Nile River originates in the Ethiopian Highlands at Lake Tana. The river flows from Ethiopia into Sudan where it joins the White Nile at Khartoum to form the Main Nile. The Blue Nile is 1529 km in length with a catchment area of approximately 330,000 km^2. The Eastern Nile River basin is composed of the Blue Nile, the Atbara, the Baro-Aboko-Sobat, the White Nile downstream from Malakal and the Main Nile sub-basins. Fig. 1 shows how the Eastern Nile River basin is represented in the model.

The flow regime of the Blue Nile is currently largely unregulated and is characterised by considerable seasonal and inter-annual variability. The natural seasonal flow distribution is slightly attenuated by storage in Lake Tana, with peak flows delayed to the period between August and September/October and proportionally higher dry season flows than along the rest of the river. Lake Tana outflow is currently controlled by the Chara Chara Weir, resulting in a change in the natural flow pattern from the lake. Higher dry season flows and lower wet season flows have resulted; however, because the flow from Lake Tana is relatively small, it has no significant impact on the distribution of downstream flows. Control of this seasonal and inter-annual flow variability is one of the main challenges in the management of the Blue Nile waters.

2.2. The SDDP model

To assess the hydrologic and economic risks faced by the downstream riparian countries, following the construction of the GERD, a stochastic hydro-economic optimisation model of the Eastern Nile River basin is developed. The model is formulated to maximise the expected economic returns associated with the allocation decisions over a given planning period, taking into account the main hydraulic infrastructure and water demands. Denoting t as the index of time (stage), T the end of the planning period, b_t the one-stage benefit function at stage t, u the vector of allocation (decision) variables, w the vector of state variables, q the vector of stochastic inflows, α the discount factor, v the terminal value function, f the transition from state t to stage $t+1$, g the set of functions constraining the decisions, and h the set of functions constraining the state, the optimisation problem can be written as

$$Z^* = \max_{u_t}\left\{ \mathop{\mathbb{E}}_{q_t}\left[\sum_{t}^{T} \alpha_t b_t(w_t, u_t) + \alpha_{T+1} v(w_{T+1}) \right] \right\} \tag{1}$$

Subject to

$$g_{t+1}(u_{t+1}) \le 0 \tag{2}$$

$$h_{t+1}(w_{t+1}) \le 0 \tag{3}$$

$$u_{t+1} = f_t(u_t, q_t) \tag{4}$$

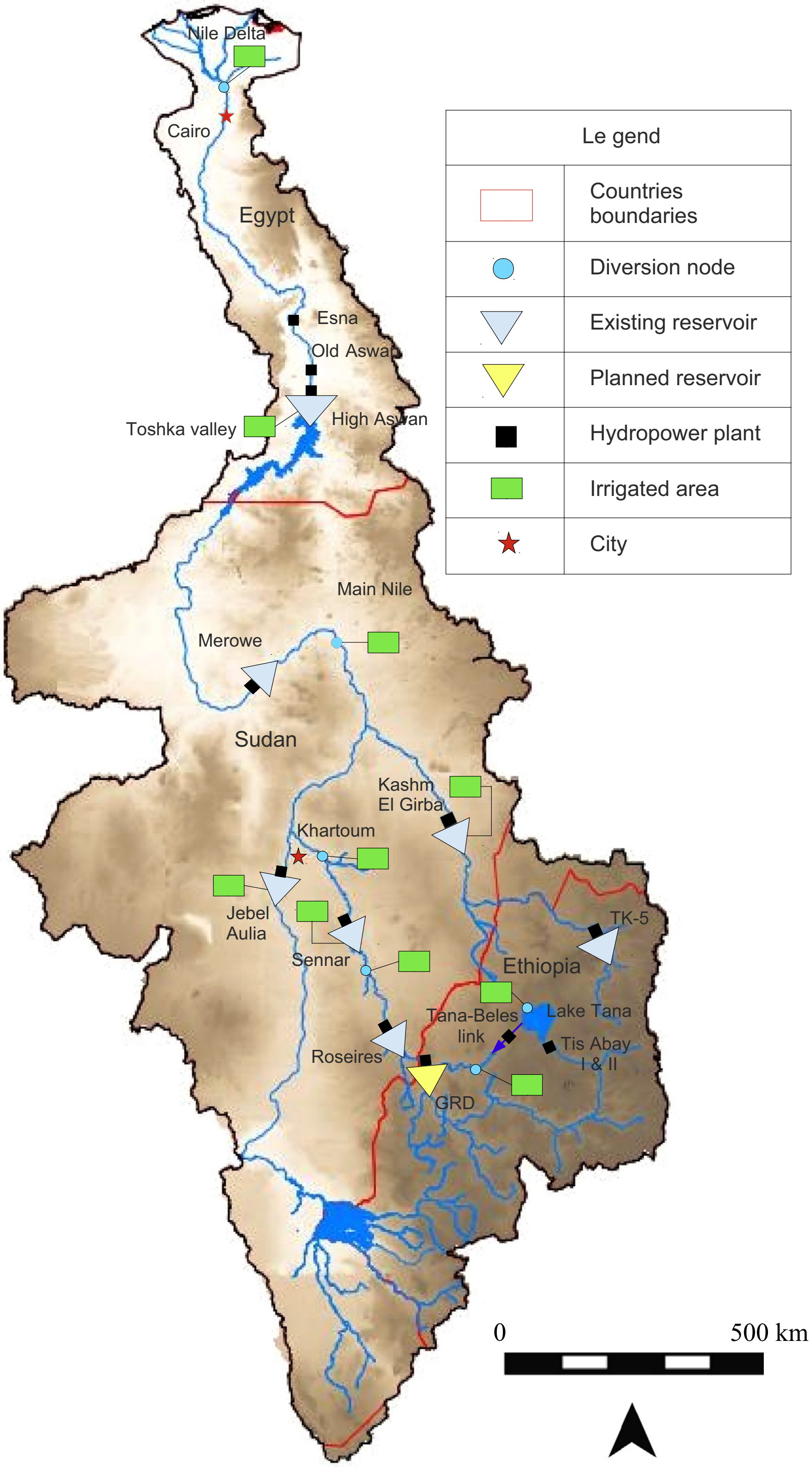

Fig. 1. Schematisation of the Eastern Nile River basin.

where $\mathbb{E}$ is the expectation operator and Z^* is the basin-wide net benefit associated with the optimal allocations $(u_1^*, u_2^*, \ldots, u_T^*)$.

The optimisation problem (1)–(4) is solved using the SDDP algorithm. As its name indicates, SDDP is an extension of stochastic dynamic programming (SDP) that removes, to a large extent, the computational limitations of SDP (the "curse of dimensionality"). The one-stage SDDP optimisation model for a water resource system whose dominant uses are hydropower generation and irrigated agriculture can be written as

$$F_t(s_t, q_{t-1}, y_t) = \max\{b_t(s_t, q_t, s_{t+1}, r_t, y_t) + \alpha_{t+1} F_{t+1}\} \tag{5}$$

where s is the vector of storage; q the vector of natural inflows; y the volume of water diverted to the irrigation schemes from the beginning of the irrigation season to the current stage t; r the vector of reservoir releases; α a discount factor; and F the benefit-to-go function. The maximisation occurs to the extent permitted by the following constraints:

The mass balance constraint:

$$\mathbf{s}_{t+1} - C^R(r_t + l_t) - C^I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t \tag{6}$$

where C^R and C^I are the connectivity matrices representing the topology of the system and the irrigation return flows, respectively; l the vector of spillage losses; e the vector of evaporation losses; and i irrigation water withdrawals. Lower and upper bounds of this constraint are defined as

$$\underline{s}_{t+1} \le s_{t+1} \le \overline{s}_{t+1} \tag{7}$$

which ensures that water levels in the reservoir do not exceed the maximum capacity ($\overline{\mathbf{s}}_{t+1}$) or the dead storage capacity ($\underline{\mathbf{s}}_{t+1}$).

The limits on reservoir releases:

$$\underline{r_t} \le r_t \le \overline{r_t} \tag{8}$$

which are introduced to ensure maximum turbining capacity of the hydropower station and to maintain minimum downstream flow for water quality, navigation etc.

The inequality constraints which are the cuts used to approximate the benefit-to-go function F_t:

$$\begin{cases} F_{t+1} - \boldsymbol{\varphi}_{t+1}^1 s_{t+1} - \boldsymbol{\eta}_{t+1}^1 y_{t+1} \le \gamma_{t+1}^1 q_t + \boldsymbol{\beta}_{t+1}^1 \\ \vdots \\ F_{t+1} - \boldsymbol{\varphi}_{t+1}^L s_{t+1} - \boldsymbol{\eta}_{t+1}^L y_{t+1} \le \gamma_{t+1}^L q_t + \boldsymbol{\beta}_{t+1}^L \end{cases} \tag{9}$$

where φ, γ, η and β are cut parameters and L is the number of cuts. Details on how the cuts' parameters are derived can be found in Goor et al. [9].

The immediate benefit function $b_t(.)$ is defined by the sum of the net benefits from energy and irrigation minus penalties for not meeting operational constraints:

$$b_t(.) = HP_t + IR_t - \xi_t' z_t \tag{10}$$

where HP is the benefits from hydropower; IR the benefits from irrigation; and z a vector of slack variables with the violations of operational constraints (energy deficit, environmental flows, etc.) which are penalised in the objective function by the vector of penalties ξ (\$/unit of deficit or surplus).

The first term on the right-hand side of Eq. (10) is the immediate short-run net benefits from hydropower generation:

$$HP_t = \tau_t \sum_{j=1}^{J} (\pi_t^h(j) - \Theta^h(j)) P_t(j) \tag{11}$$

where τ_t is the number of hours in period t; $\pi_t^h(j)$ the short-run marginal cost (SRMC) of the hydrothermal electrical system to which power plant j contributes (US\$/MWh); $\Theta^h(j)$ the O&M cost of hydropower plant j (US\$/MWh); and $P_t(j)$ (MW) the power generated by hydropower plant j during period t. In this study, we consider a seasonal short-run marginal cost (SRMC) averaging 80 US\$/MWh for firm power and 50 US\$/MWh for secondary power. These values are consistent with the feasibility studies of the hydroelectric dams in Ethiopia.

The second term on the right-hand side of Eq. (10) is the net benefits from irrigation, IR_t, which is the sum of the benefits $(\zeta_{t_f}^{(p)})(d)$ obtained for each crop p at each irrigation demand site d at the last stage t_f of the irrigation season. The net benefit at a given irrigation site is proportional to the volume of water, $y_{t_f}^{p}(d)$, that has been delivered to crop p at that site during the irrigation season:

$$IR_t = \begin{cases} \sum\limits_{d,p} \zeta_{t_f}^{p}(d) y_{t_f}^{(p)}(d) & \text{if } t = t_f \\ 0 & \text{if } t \neq t_f \end{cases} \tag{12}$$

The net benefit function $\zeta_{t_f}^{p}(d)$ associated with crop p at site d is calculated as

$$\zeta_{t_f}^{p}(d) y_{t_f}^{p}(d) = [\pi^p(d) c^p(d) - \theta^p(d)] A^p(d) \tag{13}$$

where $\pi^p(d)$ [US$/T] is the farm gate price of crop p at site d; $c^p(d)$ [T/ha] the actual yield of crop p at site d; $\theta^p(d)$ [US$/ha] the production costs of crop p at site d, and $A^d(d)$ [ha] the maximum area that can be cultivated for crop p at site d. The impact of a variation in water supply (deficit) on crop yields is assessed using a linear relationship between crop yield deficit and the actual evapotranspiration (ET_a) [8]. We further assume that the ratio between the actual and maximum evapotranspiration is approximated by the ratio between the volume of water effectively allocated to the crops (variable y_t) and the corresponding max amount. With this assumption, the state vector of SDDP includes the variable y_t, which can be considered as a “dummy” reservoir that must be refilled during the irrigation season (and depleted at the end). The continuity equation for this “dummy” reservoir is

$$y_{t+1} - \epsilon i_t = y_t \tag{14}$$

where i is the vector of irrigation withdrawals and ϵ is the vector of irrigation efficiencies.

The upper and lower bounds of these reservoirs are defined as

$$\underline{y}_{t+1} \leq y_{t+1} \leq \overline{y}_{t+1} \tag{15}$$

The “dummy” reservoir is then depleted at the end of the season (stage t_f) when crops are harvested and sold. Constraints imposed on irrigation withdrawals at stage t ensure that the allocation decisions are consistent with the capacity of the conveyance system or pumping station and with crop water requirements at that stage:

$$\underline{i_t} \leq i_t \leq \overline{i_t} \tag{16}$$

Given the lack of accurate data with respect to irrigated agriculture in the basin, a horizontal demand curve for irrigation water withdrawals is assumed with a net return of 0.05 US$/m^3, as in Whittington et al. [7].

The model includes all major reservoirs, hydropower plants and irrigation schemes in the Eastern Nile basin. Depending on the management scenario, the GERD is added to the model and irrigation areas are increased to reflect future irrigation plans in Ethiopia and Sudan. See appendices for a detailed description of the infrastructure and irrigation areas included in the model.

The model solves the water resources allocation problem using a monthly time step. To deal with the multi-year storage capacity of some of the reservoirs, we chose to work with a planning horizon of 10 years ($T=120$ months). The SDDP-derived optimal benefit-to-go functions F_{t+1} were simulated using 30 different synthetically generated sequences over this 120 month period. Historical flows were not used because of the limited length of concurrent flows at all stations (21 years). We chose, instead, to work with these artificial (synthetic) hydrological sequences. The available lateral inflows for each reservoir were used to estimate the parameters of the built-in multi-site periodic autoregressive hydrological model which were then used to generate the 30 hydrological sequences. The number of sequences is a tradeoff between computation time and the representativeness of the hydrological process. Previous studies [12] have shown that using between 30 and 50 hydrologic sequences gives similar results.

The analysis was carried out on year five results only. This ensures a “steady-state” condition that is not influenced by the initial hydrological and storage conditions or by the “end-effect” distortion as a result of reservoir depletion that happens as the end of the planning period approaches [10].

Sources of data include feasibility studies of the GERD, other hydropower plants and Lake Tana. Infrastructure data were obtained from various sources, including ENTRO, relevant ministries in the Eastern Nile region (Ethiopia, Egypt, Sudan) and consultants reports.

After convergence, the model provides a number of results for each time step at key locations throughout the basin (reservoirs, irrigation demand sites, power stations, river reaches) such as the outflows from the turbines, spillage, storage levels and evaporation losses from the reservoirs, irrigation withdrawals, irrigation return flows, river discharges, at-source and at-site marginal water values (corresponding to the dual variables (Lagrange multipliers) associated with the mass balance Eqs. (7) and (11), respectively), net benefits/costs, etc. As many simulations are carried out, it is possible to construct an empirical statistical distribution for each result.

2.3. *Development and management scenarios*

To evaluate the impact of the GERD on downstream riparian countries, four scenarios were created. These scenarios represent either different levels of development of the river basin, in terms of water usage, or alternative management strategies/arrangements. In the case of development scenarios (scenarios 1, 2 and 4 below), full cooperation is assumed, meaning that there is coordinated operation of all basin infrastructure to optimise the total basin-wide economic benefits. This follows Whittington et al. [7] who judge that full infrastructure development on the Nile, and to operate these to maximise economic benefits, would be impossible without full cooperation among the riparians. Wu and Whittington [21] also point out that Egypt's benefits from cooperation are significant and that it is most at risk from unilateral actions by upstream countries. The alternative management scenario (scenario 3 below) represents an intermediate level of cooperation. Taken individually, some of the scenarios might not be relevant, but their comparison with the other scenarios is often informative.

First, a baseline scenario (S1) represents the current infrastructure situation in the basin. This scenario assumes that the production of hydroelectricity is coordinated at the basin scale, however, individual countries still give priority to agricultural uses.

The second scenario (S2) differs from S1 in that the GERD is now online; all other parameters remain unchanged. Comparing S2 to S1 will reveal the impacts of the GERD on the rest of the system, especially on the agricultural and energy sectors in Sudan and Egypt. One of the advantages of stochastic optimisation is that statistical distributions of selected performance indicators, such as energy generation or cross-border flows, can be derived and the risk of failure assessed.

The third scenario (S3) corresponds to a situation in which the GERD would be operated to maximise energy revenues in Ethiopia only, regardless of downstream water demands. Note that the irrigation sector is identical to that found in S1 and S2. Comparing this scenario to S2 will reveal the extent of the risk (and the cost) faced by downstream countries in the case of the unilateral operation of the GERD.

The fourth scenario (S4) is based on S2 but with major expansions of the irrigation schemes in Sudan and Ethiopia. In this scenario, the assumption was made that Sudan fully uses its share of the 1959 agreement while Ethiopia goes ahead with the planned irrigation projects around Lake Tana [11]. Comparing S4 to S2 indicates, among other things, the hydrologic risk exposure of Egypt to upstream withdrawals. This comparison, contrasted with the pair (S1–S2), determines whether the GERD attenuates or exacerbates the impacts.

3. Results and analysis

3.1. *Drawdown-refill cycles*

The drawdown-refill cycles for the GERD, in scenarios S2, S3 and S4, are illustrated in Fig. 2. SDDP-derived storage volumes for each hydrologic sequence are shown as points, the height of the box corresponds to one standard deviation from the mean (i.e.: the 68% confidence interval assuming that

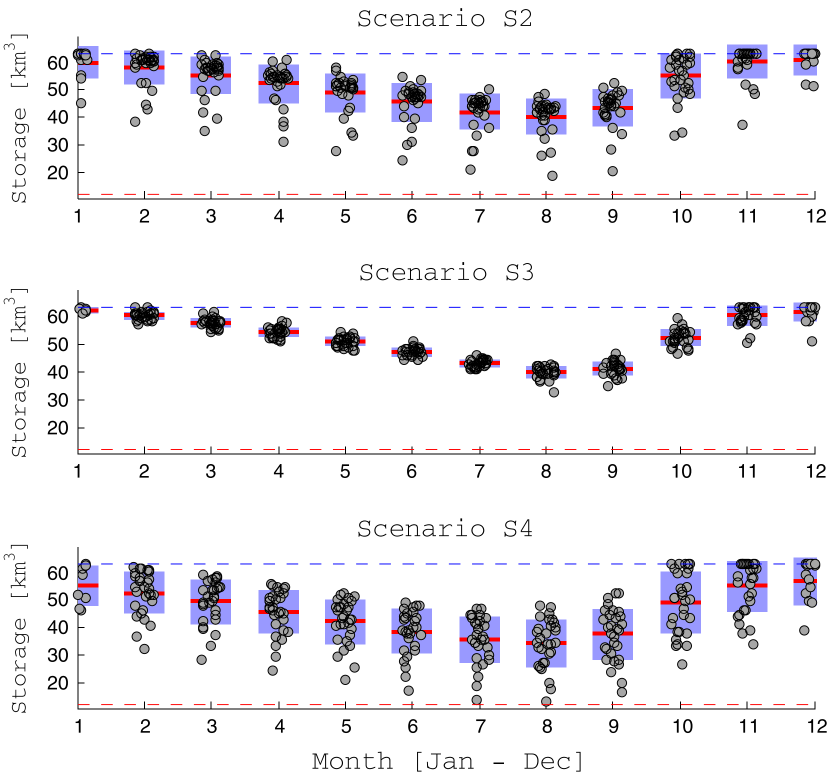

Fig. 2. Drawdown-refill cycles for the GERD. S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

the storage volumes are normally distributed) and the band near the middle of the box indicates the mean storage volume. The dashed lines at the top and bottom of each graph mark the high storage and low storage levels, respectively, in the reservoir. We see that the drawdown-refill cycle, for each scenario, is typical of hydroelectric reservoirs with constant depletion during the dry season followed by a quick refill during the high flow season (August – November). It is also interesting to note that the GERD, once online, is expected (on average) to exploit about one half of its storage capacity. This is a trade-off between keeping the pool elevation high for increased productivity of the power plant and releasing water for flow regulation downstream. We can also see that the general shape of the cycle is mostly unaffected by the development/management scenarios. In S2 the GERD is operated in conjunction with the other infrastructure in the basin (mostly the Aswan High Dam (AHD)) and the storage levels tend to be more variable (as seen by the spread of the points at each month). This means that water held in storage at the GERD is being used to balance irregular flows downstream. In contrast, when the GERD is operated to maximise the net benefits from hydropower generation in Ethiopia only (S3), the year-to-year variability of the storage levels at the GERD is nullified. The GERD is no longer being used to balance downstream flows, only to maximise hydropower output at this site, thereby ensuring constant yearly power generation for Ethiopia. In S4, with increased upstream irrigation demand, a noticeable decrease in storage is observed. The levels are lower overall and the variability greatly increases. In fact, we see that under very dry conditions, the reservoir may drain almost completely (down to the low storage level defined in the model).

The drawdown-refill cycles of the AHD, under each management scenario, are illustrated in Fig. 3. In the current situation (S1) the year-to-year variability is significant, as there is no upstream infrastructure with multi-year storage capacity to regulate flow. When the GERD is online (S2), the AHD is operated at a higher and more constant level due to upstream regulation by the GERD. As well, the model calculates that the hydropower benefits from keeping a higher head on the turbines at the AHD outweigh the losses from evaporation due to these higher storage levels. The unilateral management of the GERD (S3) results in pool elevations at the AHD being slightly higher than in the current scenario (S1) but lower than when the GERD is coordinated (S2). There is a greater variability

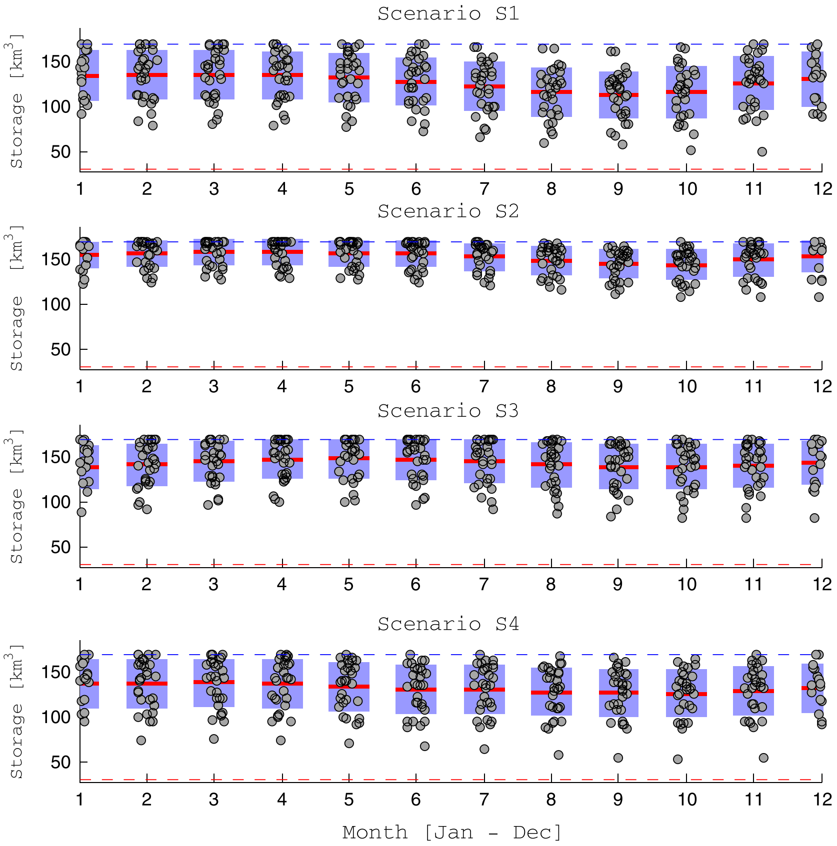

Fig. 3. Drawdown-refill cycles for the AHD. S1=Baseline scenario; S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

in storage levels because the AHD must manage variations in flow levels as this is only partially accomplished by the GERD in this scenario. As a result of increased irrigation withdrawals upstream (S4), we see the AHD being operated at lower pool elevations with greater variability. With greater water abstractions upstream, the system is optimised to save water by reducing storage at the AHD, thereby reducing evaporation losses.

3.2. *Evaporation losses*

Annual evaporation losses in Ethiopia, in all scenarios, are about 800 hm^3, which corresponds to about 1% of the annual flow of the Nile. This is a result of the lower temperatures and greater rainfall that characterise the headwater region of the Blue Nile. In all of the management scenarios, losses in Egypt are much more significant, ranging from 11.5 km^3/yr to 12.3 km^3/yr. Higher evaporation values are observed when the GERD is online (S2) due to the AHD being operated at a higher level. Overall, evaporation losses are equivalent to $>20\%$ of the 84 km^3/yr total Nile flow that was used to calculate the allocations to Egypt and Sudan in the 1959 agreement. In Sudan, the combined losses from Roseires, Sennar and Merowe are around 2.3 km^3/yr. These losses remain fairly constant across all scenarios because, in contrast to Egypt and Ethiopia, the relatively low storage capacity in Sudan does not allow for major changes in the monthly operation of those reservoirs, resulting in little change in evaporation losses.

3.3. *Hydrological risk*

Outflows from the GERD and the AHD are shown in Figs. 4 and 5, respectively. These graphs display the statistical distribution of outflows from the two reservoirs. The empirical cumulative distribution

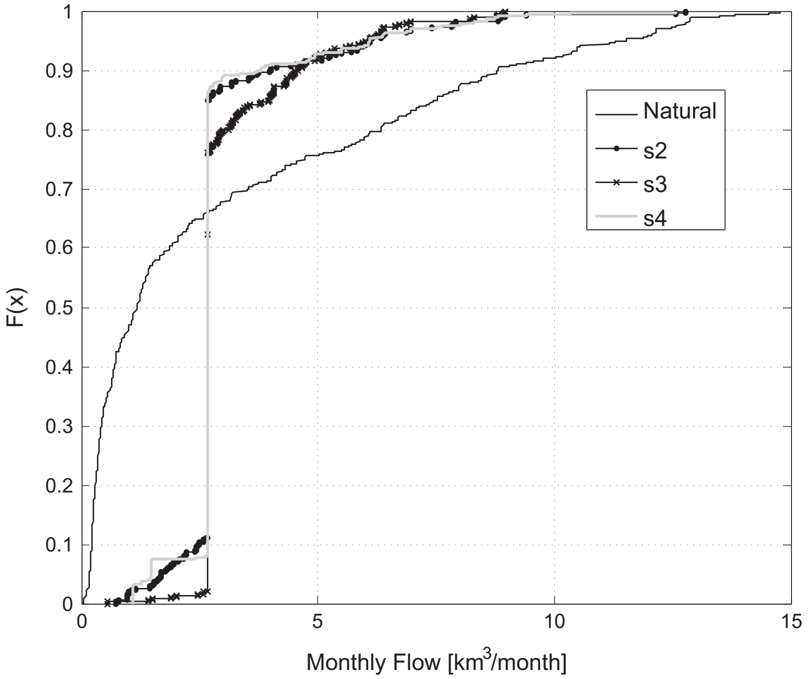

Fig. 4. Monthly outflow GERD. S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

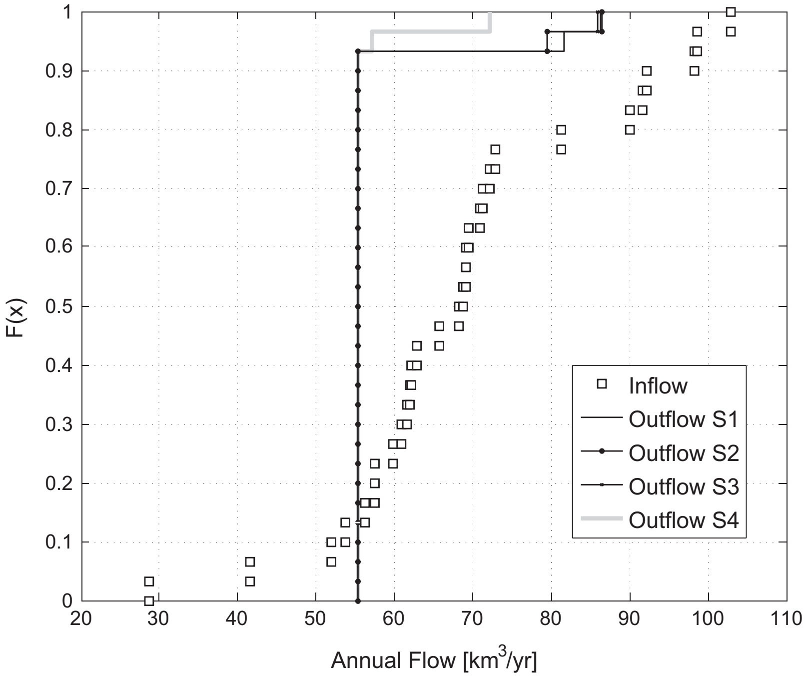

Fig. 5. Annual outflow AHD. S1=Baseline scenario; S2=GERD online; S3=Unilateral operation of GERD; S4=Irrigation expansion in Sudan and Ethiopia.

functions (CDF) give the non-exceedance probability $F(X)$ of any given outflow (X). Monthly outflows are presented for the GERD to show the regulation capacity of this infrastructure, while annual outflows are presented for the AHD to allow comparison with the annual allotment from the 1959 agreement.

Not surprisingly, with the GERD online (S2), low flows are augmented to the extent that about 3 km^3/month are secured at least 90% of the time ($F(X)=0.1$), compared to only 35% of the time ($F(X)=0.65$) under natural conditions (Fig. 4). High flows are decreased with the monthly outflow reduced by a factor of two, from about 8 km^3 to 4 km^3, at an exceedance probability of 10% ($F(X)=0.9$). A more constant water supply to Sudan and Egypt is ensured, thereby reducing their hydrologic risk exposure to droughts and floods. This is especially important for Sudan due to the limited water storage capacity within the country, which is not the case for Egypt with the large storage capacity of the AHD. These results are similar to those found by McCartney et al. [11] and Goor et al. [9], who show a significant reduction in wet season flow and increases in dry season flow due to regulation from hydropower infrastructure at the Ethiopia/Sudan border.

Results for the AHD (Fig. 5) show that the minimum annual outflow would be at least 55 km^3/yr, which is equivalent to the amount allocated to Egypt in the 1959 agreement, and this holds true for all scenarios. In other words, when the operation of the GERD reaches a steady state, this infrastructure poses no threat to Egypt's water supply. Even with the planned irrigation expansions in Sudan and Ethiopia (S4), the risk of failure is nullified due to the over-year storage capacity of the AHD. This is confirmed by plotting the statistical distribution of Lake Nasser's annual inflows against the annual allotment. We see that the hydrological risk faced by Egypt, in the absence of the GERD, is about 13% (where inflow and S2 meet). Nullifying the hydrological risk in Egypt, by increasing storage at the AHD, has an opportunity cost corresponding to the benefits forgone from the resulting increased evaporation losses from Lake Nasser.

3.4. Hydropower generation

Per country annual energy production in the BlueNile/Nile are presented in Table 1. Increases in energy production of 15% and 2% are shown in Sudan and Egypt, respectively, when the GERD is online (S2), as a result of reduced spillage and higher pool elevations in the reservoirs located downstream of the GERD. The lack of coordination in reservoir operation (S3) yields a 4% reduction in power output from the Sudanese generators with negligible gains and losses in Ethiopia and in Egypt respectively. The impact of irrigation expansion (S4) falls, essentially, on Egypt (−3% of energy output) due to decreased storage levels at the AHD. Ethiopia is mostly unaffected because the increase in net irrigation consumptive uses around Lake Tana is not significant (<200 hm^3) compared to river flow at the GERD. Sudan is also mostly unaffected since storage capacity is limited in the country and reduced monthly discharges, due to upstream water withdrawals, implies lower spillage losses.

3.5. Annual net benefits

To better understand the exposure of downstream countries to the GERD, the statistical distributions of the combined net benefits in Sudan and Egypt are displayed in Fig. 6. In the current situation (S1), the combined benefits range from 4.9 billion US$/yr to 6 billion US$/yr depending on whether the hydrologic conditions are dry or wet. When the GERD is online, minimum benefits in the downstream countries increase to about 5.6 billion US$/yr while the maximum remains unchanged. This indicates the positive role played by the GERD during dry years and its ability to increase water supply to these downstream countries under adverse hydrologic conditions. Even in average years ($F(X)=0.5$) we see a slight increase in the net benefits, compared to the current situation. Irrigation expansion in Sudan and Ethiopia (S4) yields an increase of about 180 million US$ which remains fairly

Table 1
Annual energy production (TWh).

	S1	S2	S3	S4
Ethiopia	1.44	16.05	16.15	16.06
Sudan	8.29	9.52	9.12	9.27
Egypt	13.96	14.15	14.14	13.68

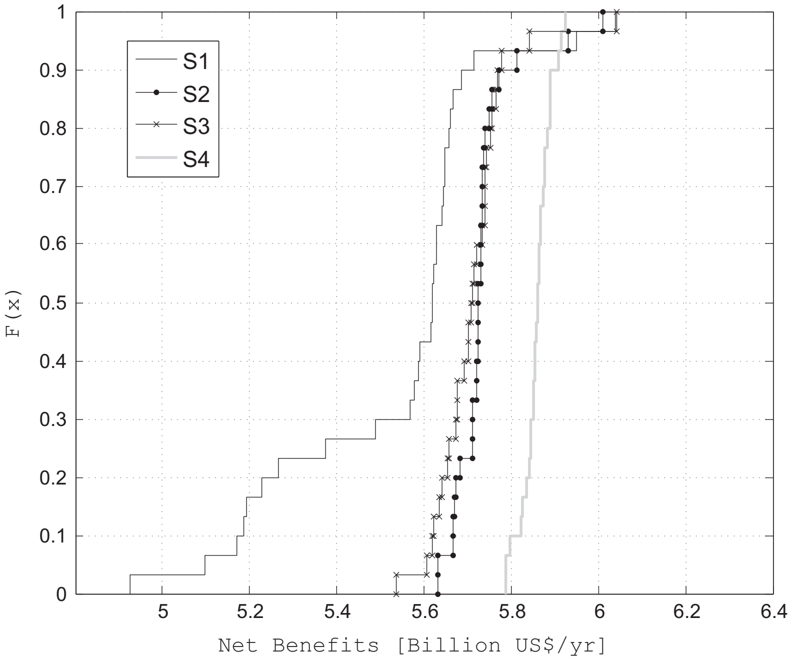

Fig. 6. Net benefits in Sudan and Egypt. S1 = Baseline scenario; S2 = GERD online; S3 = Unilateral operation of GERD; S4 = Irrigation expansion in Sudan and Ethiopia.

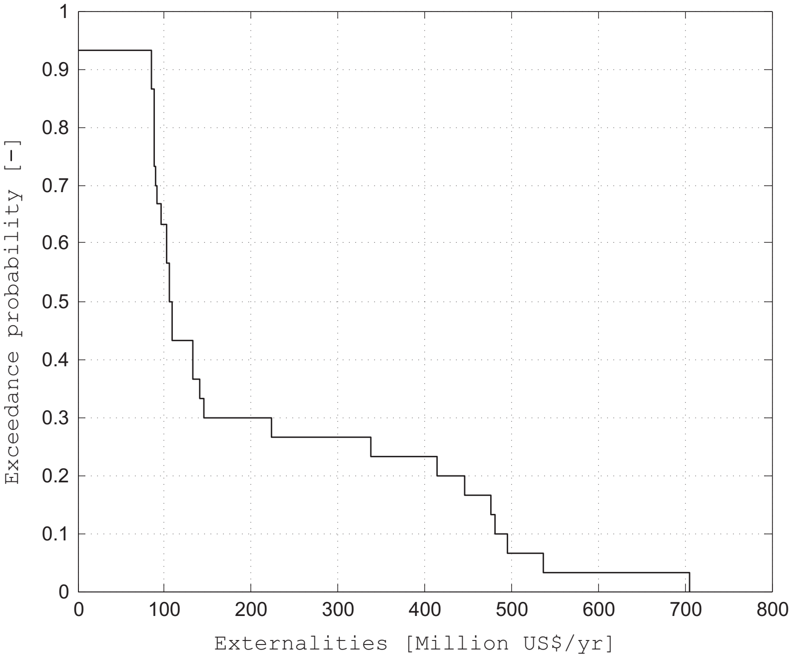

Fig. 7. Externalities in Sudan and Egypt.

constant throughout the hydrologic scenarios. Note that this would no longer be true if consumptive uses increase beyond the amount of renewable water in the system (not shown here). In general, the total net benefits in Sudan and Egypt become more constant over all hydrologic scenarios when the GERD is online.

Of interest is the horizontal difference between the statistical distributions of net benefits in the current situation (S1) and when the GERD is online (S2) (Fig. 7). This gives the statistical distribution of the externalities associated with the GERD on the agricultural and energy sectors in Sudan and

Egypt. 90 million US$/yr in benefits is secured at least 90% of the time, 145 million US$/yr will be exceeded 30% of the time, and 500 million US$/yr will be ensured in at least one year out of ten.

4. Conclusions

The main purpose of this study is to assess the positive and negative externalities associated with the GERD on downstream Egypt and Sudan, assuming that the GERD has reached steady-state. Our results show that there are numerous benefits to be had by downstream countries, especially during dry years. Note that the filling phase of the reservoir under normal hydrologic conditions is studied in Mulat and Moges [27]. With increased storage in Ethiopia, Egypt and Sudan can expect greater net benefits from irrigation and hydropower, and can also gain through reduced flooding and droughts. One of the main benefits lies in the ability of the GERD to remove the hydrological uncertainty inherent during periods of low flow. It is, however, imperative that there is full cooperation between the 3 basin countries in order to realise these benefits.

This study did not include all other downstream impacts of the GERD, such as positive impacts as a result of lower sediment load, or negative impacts on flood plain agriculture along the Nile. Caveats of the model used in this study include (1) that demand curves are simplified (due to a lack of data); (2) that the model does not handle inter-annual flow variability; (3) that SDDP provides only approximate solutions (exact solutions are not available for such large stochastic problems); (4) that SDDP mimics a centralised decision-making process, assuming full cooperation between agents. Each of these conditions either overestimates or underestimates the benefits or the performance of the system. For example, the fact that SDDP provides only approximate solutions tends to underestimate the benefits while the assumption of full cooperation will overestimate the benefits. It is, therefore, difficult to determine the implications of these conditions/limitations on the results as their effects may cancel each other out.

Despite these limitations, this model can be used to assess the effects of new infrastructure on regional water systems or to efficiently reallocate water among existing uses so that the net benefits to the system are maximised. Further research to establish true demand curves for the study site would certainly provide added value to this tool. As well, levels of cooperation, other than that explored in this study, could be assessed. Although this study, as well as many others, show that all riparians in the Eastern Nile basin stand to gain from full cooperation, intermediate levels of cooperation should be assessed since the ideal situation of fully cooperative riparian countries has been elusive in the Nile basin and will likely be difficult to reach in the vast majority of international river basins.

Appendix A. Reservoirs and hydropower plants

The Eastern Nile hydro-system is currently made up of eleven major hydraulic infrastructure (as detailed in Table A1).

Ethiopia – The first structure in Ethiopia is the Chara Chara weir which regulates outflows from Lake Tana to the Tis Abbay power complex, located approximately 32 km downstream. The Tana-Beles scheme, which was started in May 2010, is an artificial link between Lake Tana and the Beles river. This link generates hydroelectricity and has a potential to irrigate land in the future. In the upper Ethiopian section of the Atbara sub-basin (known as the Tekeze river in Ethiopia), the TK-5 dam is the largest Ethiopian hydraulic infrastructure. With an over-year storage capacity of 9.23 km^3 and an installed capacity of 300 MW, the TK-5 dam came online in 2009 and is expected to produce approximately 30% of the current total national electricity production.

Sudan – Downstream, in Sudan, the Roseires and Sennar dams provide seasonal regulation of the Nile waters for the irrigation of more than 1 million ha of crops distributed over 6 major schemes. The associated hydropower stations supply electricity to Sudan but, given the low head available, production is relatively small.

Table A1
Major existing infrastructure: hydropower plants and reservoirs [13,14,7].

Name (Country)	River	Live Storage (hm^3)	Capacity (MW)
Tis Abbay I and II (ET)	Blue Nile	ROR	86
Tana-Beles link (ET)	Blue Nile	ROR	270
Tekeze (ET)	Atbara	9200	300
Roseires (SU)	Blue Nile	6900	275
Sennar (SU)	Blue Nile	480	15
Khashm El Girba (SU)	Atbara	630	17
Jebel Aulia (SU)	White Nile	2800	30
Merowe (SU)	Main Nile	8300	1250
Aswan High Dam (EG)	Main Nile	105,900	2100
Old Aswan Dam (EG)	Main Nile	ROR	500
Esna (EG)	Main Nile	ROR	90

ROR = run-of-river power plant, ET = Ethiopia, SU = Sudan, EG = Egypt, 1 hm^3 = 1 million m^3.

Due to its physiographic characteristics, Sudan has only a few interesting sites at which to store water and produce electricity, and suffers from a lack of over-year storage capacity for irrigation supply and to reduce flood damage. To tackle this problem, the heightening of the Roseires dam, completed in January 2013, increased its storage capacity to 6.9 km^3. The Atbara river is dammed at Khashm El Girba. Here, the installed capacity is relatively small and the reservoir is encountering a reduction in storage capacity due to siltation. Two new dams (Rumela and Berdana) are under construction across the two branches of the Atbara river (Setit and Upper Atbara). Impounding is expected in 2014, to provide 300 MW of capacity as well as water supply for existing and new irrigation schemes. Located on the White Nile, near its confluence with the Blue Nile, the Jebel Aulia dam is presently operated to reduce pumping costs for the irrigated areas located around the reservoir. The Merowe dam, with an installed capacity of 1250 MW, came on-line in 2009 and has significantly increased the Sudanese production of hydroelectricity.

Egypt – In Egypt, the Aswan High Dam (AHD) is the largest infrastructure in the basin and it fully regulates the Nile waters downstream of the dam. Its over-year storage capacity, and associated hydropower plant, were designed to supply reliable irrigation water, to meet increasing energy demand (around 9% of the current total national electricity production), to improve downstream navigation and to protect Egypt against flooding. The downstream Aswan High Dam (the Old Aswan dam) is operated as a run-of-river plant, regulating, slightly, the daily outflows from the AHD and contributing to the production of electricity. The Esna run-of-river plant is the most recent significant hydropower facility on the main Nile.

The major challenge, with respect to the management of the Nile waters, is to control the seasonal and inter-annual variability. To date only relatively small hydraulic infrastructures have been constructed in the Blue Nile catchment in Ethiopia, despite the huge hydropower potential offered by the topography of the country. However, since the beginning of the 20th century, large-scale projects have been on the drawing board to develop the upper part of the basin [15].

Under the umbrella of the NBI, a joint study was initiated to develop the Blue Nile in Ethiopia. The projects included the development of 4 major hydropower plants and reservoirs: Karadobi, Mabil, Mandaya and Border. The objectives of the proposed joint multipurpose projects are to increase flow reliability, to generate cheap hydropower and enhance downstream energy production, to alleviate downstream sedimentation and to mitigate floods and droughts along the Nile and the Blue Nile. The projects are expected to boost the production of hydroelectricity and will probably have significant impacts on the management of the Nile waters.

Currently, the Border project has been replaced by the GERD.

Appendix B. Irrigated areas

Agriculture is the largest consumptive use of water in the Nile basin. In Egypt and Ethiopia, agriculture accounts for about 86% of water withdrawal while, in the case of Sudan (including South

Sudan), it is closer to 94% [16]. Rainfall contributes significantly to agricultural water in the Great Lakes region, but is scarce in the lower regions of the river, which depend mainly on river water and groundwater.

To achieve food security, as a result of rapid population growth, Nile basin countries will require more and more water for irrigation [17]. In the early 1990s, Egypt's total water use was 65 km^3/yr, with 55 km^3/yr being withdrawn from the Nile River. By the year 2000, water demand had increased to 73.3 km^3/yr, of which 60.7 km^3/yr was for agricultural demand. It is projected that, by 2025, agricultural water demand will be 69.4 km^3/yr out of a total water demand of 86.9 km^3/yr [18]. The New Valley project, currently under construction in the Western Desert, is designed to irrigate 250,000 ha of crops by pumping water from Lake Nasser.

Sudan's population is growing at an annual rate of 2% and 70% of this population is dependent on agriculture. Sudan has managed to cultivate only 16.7 million ha out of a potential 105 million ha. Moreover, only 1.9 million ha of this land is irrigated, out of a possible 2.8 million ha. It is estimated that, by the year 2025, Sudan's demand will be in the order of 32 km^3/yr, due mainly to increased irrigation requirements [19].

Irrigation in Sudan is organised around six major schemes. Along the Blue Nile, water is pumped between the Roseires and Sennar dams for the irrigation of about 300,500 ha of crops. The Sennar reservoir feeds the Gezira–Managil scheme, which is found on the left bank of the Blue Nile. This is the largest irrigated area in Sudan (870,000 ha) and the only gravity irrigation scheme along the Blue Nile. Water is pumped from the Blue Nile, between Sennar and Karthoum, in order to irrigate 74,500 ha of crops. On the White Nile, about 180,000 ha are currently being irrigated by water pumped from the Jebel Aulia reservoir. The New Halfa scheme (113,000 ha), located downstream of the Khashm El Girba reservoir, was established for the resettlement of Sudanese farmers as a result of the filling of Lake Nasser. The last significant scheme is located along the Main Nile, downstream of Karthoum, with 80,000 ha of cultivated area.

Agriculture, primarily rain-fed, with very little irrigation, is the main occupation for Ethiopians living in the Nile basin. Ethiopia currently cultivates only 4% of the potentially irrigable land in the country, and only 1% of the irrigable land in the Nile basin. Ethiopia has regularly experienced large shortfalls in food production, leading to increased importation of food. In the last 25 years, the country has seen two severe famines. The Ethiopian government insists that the utilisation of the Nile River waters is essential for socio-economic development and poverty reduction and are serious about achieving self-sufficiency in food production, at any cost [17].

Some potential irrigation developments exist directly in the Ethiopian part of the Blue Nile basin, but they are relatively limited in size. The variable topology of the Ethiopian highlands, with steep slopes and deep incised valleys, limits the possibilities for cheap irrigation. Consequently, with the exception of very small areas, none of the proposed irrigation sites take water directly from the Blue Nile. Rather, around 150 000 ha are planned around the Beles River [20].

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II

Sharing Water and Benefits in Transboundary River Basins

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Le partage équitable des bénéfices dans les bassins fluviaux transfrontaliers est nécessaire pour résoudre les conflits entre les pays riverains et atteindre un consensus sur les activités de développement et de gestion du bassin. Le partage des bénéfices doit être discuté collectivement par tous les pays riverains pour être perçu non seulement comme efficace, mais aussi équitable. La littérature actuelle décrit principalement ce que l'on entend par le partage des bénéfices des bassins fluviaux transfrontaliers d'un point de vue conceptuel, mais propose peu d'approches pratiques et institutionnelles, de même que des méthodes collaboratives pour encourager le partage équitable de ces bénéfices. Dans cette étude, nous proposons un arrangement institutionnel pour la répartition des bénéfices d'un bassin fluvial transfrontalier en maximisant d'abord les avantages économiques de l'utilisation de l'eau puis leur répartition équitable à partir d'une méthode où les parties prenantes sont impliquées. Nous décrivons une méthodologie dans laquelle (i) un modèle hydrologique est utilisé pour l'allocation de ressources limitées en eau d'une manière économiquement efficace aux usagers, (ii) ceux-ci sont tenus de payer des redevances pour l'eau qu'ils reçoivent, et (iii) le total de ces redevances est équitablement redistribuée sous forme de compensation monétaire aux utilisateurs par l'application d'une méthode de partage basée sur l'implication des parties prenantes et leur perception de l'équité, en utilisant une approche axiomatique. Avec la méthode de partage des bénéfices proposé, le rapport efficacité/équité existe toujours, mais l'ampleur du déséquilibre est réduite puisque que les avantages sont maximisés et redistribués selon une entente convenue préalablement par les participants. L'ensemble du système est supervisé par une autorité du bassin fluvial. La méthodologie est appliquée sur le bassin oriental du Nil comme une étude de cas. La technique décrite assure non seulement l'efficacité économique, mais peut également mener à des solutions plus équitables dans le partage des bénéfices dans les bassins fluviaux transfrontaliers. En effet, la définition de la règle de partage n'est pas contestée comme pour d'autres méthodes existantes qui comportent leurs définitions inhérentes de l'équité, telles que la théorie des jeux.

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Sharing water and benefits in transboundary river basins

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Abstract. The equitable sharing of benefits in transboundary river basins is necessary to solve disputes among riparian countries and to reach a consensus on basin-wide development and management activities. Benefit-sharing arrangements must be collaboratively developed to be perceived not only as efficient, but also as equitable in order to be considered acceptable to all riparian countries. The current literature mainly describes what is meant by the term benefit sharing in the context of transboundary river basins and discusses this from a conceptual point of view, but falls short of providing practical, institutional arrangements that ensure maximum economic welfare as well as collaboratively developed methods for encouraging the equitable sharing of benefits. In this study, we define an institutional arrangement that distributes welfare in a river basin by maximizing the economic benefits of water use and then sharing these benefits in an equitable manner using a method developed through stakeholder involvement. We describe a methodology in which (i) a hydrological model is used to allocate scarce water resources, in an economically efficient manner, to water users in a transboundary basin, (ii) water users are obliged to pay for water, and (iii) the total of these water charges is equitably redistributed as monetary compensation to users in an amount determined through the application of a sharing method developed by stakeholder input, thus based on a stakeholder vision of fairness, using an axiomatic approach. With the proposed benefit-sharing mechanism, the efficiency–equity trade-off still exists, but the extent of the imbalance is reduced because benefits are maximized and redistributed according to a key that has been collectively agreed upon by the participants. The whole system is overseen by a river basin authority. The methodology is applied to the Eastern Nile River basin as a case study. The described technique not only ensures economic efficiency, but may also lead to more equitable solutions in the sharing of benefits in transboundary river basins because the definition of the sharing rule is not in question, as would be the case if existing methods, such as game theory, were applied, with their inherent definitions of fairness.

1 Introduction

With growing water scarcity, as a result of expanding population demand, environmental concerns and climate change effects, there is increased international recognition of the importance of cooperation for the effective governance of water resources. This is particularly evident in the case of transboundary river basins in which unidirectional, negative externalities, caused by the upstream regulation of the natural flow, often place some parties at a disadvantage and result in asymmetric relationships that add to the challenge of coordinating resource use (van der Zaag, 2007). There is a consensus among water professionals that the cooperative management of shared river basins should provide opportunities to increase the scope and scale of benefits (Phillips et al., 2006; Grey and Sadoff, 2007; Leb, 2015), stepping beyond the volumetric allocation of water that reduces negotiations between riparians to a zero-sum game. In their seminal paper, Sadoff and Grey (2002) discussed the types of benefits that river basins can provide, assuming cooperation: *benefits to the river* can result from sustainable cooperative management of the ecosystem; efficient, cooperative management and development of river flow can yield *benefits from the river* in the form of increased water quality, quantity and productivity; policy shifts away from riparian disputes/conflicts toward cooperative development can reduce costs of noncooperation arising *because of the river*; and cooperation between riparian states can lead to economic, political and institutional integration, resulting in *benefits beyond the river*.

A large proportion of past research has focused mainly on the economic benefits of cooperation (benefits from the river). Focussing on benefits in strictly economic terms does not lessen the importance of benefits from other spheres (Qaddumi, 2008). An economic perspective, however, may be an effective method for encouraging cooperation because it may help riparian countries to realize win–win situations (Dombrowsky, 2009).

The traditional approach to estimating the economic benefits of cooperation relies on hydro-economic modeling (Arjoon et al., 2014; Jeuland et al., 2014; Tilmant and Kinzelbach, 2012; Teasley and McKinney, 2011; Whittington et al., 2005). These studies present various implementation strategies representing various levels of cooperation, but all show that there are significant economic benefits to be had through basin-wide cooperation. However, economic efficiency is not necessarily compatible with equitability due to the different production abilities of water users (Wang et al., 2003). Analytical methods, including game theory solutions such as the Shapley value (Jafarzadegan et al., 2013; Abed-Elmdoust and Kerachian, 2012) and bankruptcy theory (Sechi and Zucca, 2015; Mianabadi et al., 2014, 2015; Madani et al., 2014; Ansink and Weikard, 2012), have been examined for use in water allocation as equitable alternatives to the efficient economic allocation produced by hydro-economic models. Analytical methods were also used by van der Zaag et al. (2002), who looked at possible equitable criteria for sharing water and developed allocation algorithms to operationalize these, applying them to the Orange, Nile and Incomati rivers. It has been argued that the notion of equity, or fairness, involves a cultural component that should be incorporated into any type of water policy and, therefore, stakeholder involvement in decision-making is a significant determinant in the judgement of fairness (Syme et al., 1999; Asmamaw, 2015). The explicit provision of benefit-sharing arrangements that are collaboratively developed and, thus, perceived as fair, is therefore necessary to help solve disputes and to reach a consensus in transboundary river basin development and management activities (MRC Initiative on Sustainable Hydropower, 2011).

Increasingly, efforts are focussing on the sharing of benefits generated through cooperation in order to solve the problem of equitability. The rapidly growing body of literature on benefit sharing mainly describes what is meant by this in the context of transboundary river basins and discusses benefit sharing from a conceptual point of view (Suhardiman et al., 2014; Skinner et al., 2009; Qaddumi, 2008). This literature introduces and defines different approaches but falls short of providing practical institutional arrangements for the sharing of benefits. Recently, Ding et al. (2016) introduced a methodology to address the problem of water allocation in the Nile River through a revenue re-distribution mechanism that leads to a fairly allocated revenue for each water user based on the proportion of its contribution to the basin.

Analytical methods, such as game theory and related bankruptcy methods, may also be useful for determining ways to fairly allocate generated benefits. Game theory, which is the mathematical study of competition and cooperation, can provide a somewhat realistic simulation of the interest-based behavior of stakeholders (Madani, 2010). The framework that relates the preferences of players to the observable features of a game is the hypothesis that players care about nothing except their own payoffs (Hausman, 1999). Fair outcomes are captured in solution concepts such as the *core*, which selects the payoff allocations that give each group of individuals no less than their collective worth and the *Shapley value* in which payoffs are related to the marginal contributions of individuals to a coalition (de Clippel and Rozen, 2013). The aim of bankruptcy methods is to distribute an estate or asset among a group of creditors, all having a claim to the asset, where the sum of the creditors' claims is larger that the amount available to distribute (Herrero and Villar, 2001). An overview of bankruptcy rules has been presented by Thomson (2003, 2013). Each bankruptcy rule defines fairness based on the properties underlying the rule. The three most well-known bankruptcy rules (the proportional rule, the constrained equal awards rule and the constrained equal losses rule) all define equity through the *equal treatment of equals* requirement in which agents with identical claims should be treated the same[1]. In other words, agents with the same claim should receive the same compensation. The analysis and formulation of properties and principles of distribution rules, such as those in cooperative game theory and bankruptcy theory, are the object of the axiomatic method (Thomson, 2001).

The axiomatic method allows desirable properties to be translated into a sharing rule. If a particular rule has been adopted to solve a problem involving a group of agents, it is assumed that all agents have agreed on the properties that such a rule fulfills. The concept of fairness, then, can be embedded into a rule. The axiomatic approach is easily incorporated into negotiations because the axioms can be interpreted quite naturally as describing characteristics of a negotiation procedure (Ansink and Houba, 2014).

As discussed previously, the economically efficient allocation of water is not necessarily equitable. Axiomatic approaches, on the other hand, allow the characterization of an equitable distribution of welfare, but do not necessarily maximize the aggregated economic welfare over the basin. Institutional arrangements that ensure maximum economic welfare, as well as the equitable sharing of these benefits over the basin, are required.

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[1] Equal treatment of equals is one of the properties upon which these bankruptcy rules are defined. For a complete discussion of all properties, refer to Thomson (2003, 2013).

In this study we define an institutional arrangement that distributes welfare in a river basin by maximizing the economic benefits of water use and then sharing these benefits in an equitable manner. The methodology relies on a pseudo-market arrangement in the form of a highly regulated market in which the behavior of water users is restrained to control externalities associated with water transfers and to ensure basin-wide coordination and enhanced efficiency. The term pseudo-market indicates that bulk water users are not free to choose how much water will be moved in the system. Freedom of contract and private property rights, which are necessary conditions for the existence of a market, are restrained, giving rise to a pseudo-market[2]. These restrictions are due to the flow characteristics of water and to the need to account for externalities and third-party effects, which can seldom be achieved within a traditional market.

The institutional arrangement described in this paper should encourage full cooperation between water users because it is intended as a replacement for traditional types of agreements on international river basins, which can lead to distrust and tension between riparian countries. What we present is an entirely different perspective that may help to avoid the pitfalls and limitations of current agreements.

In the following section, we describe this arrangement, which uses a hydro-economic model to determine the economically efficient allocation of water and a collaboratively developed sharing method for the equitable allocation of monetary benefits. Section 3 presents the application of this framework to the Eastern Nile River basin. Section 4 presents and discusses the results and Sect. 5 concludes the paper.

2 Methodology

In the proposed pseudo-market approach, a river basin authority (RBA) plays the role of water system operator, identifying economically efficient allocation policies that are then imposed on the agents (water users). The agents are charged for water use and these payments are redistributed to ensure equitability among the users. In this particular system, the mandate of the RBA consists of (1) collecting information on water use and productivity, (2) efficiently allocating water between the different agents in the system based on the information collected in the first step, (3) preserving the hydrologic integrity of the river basin, and (4) coordinating the collection and redistribution of the benefits associated with the optimal allocation policies.

2.1 Information collection

In this first step, the RBA collects information that is required to assess the demand curves, or at least the productivity (unit net benefit), of all users in the system, once at the beginning of each year. The information must be validated to ensure that it is complete and reasonable since the economically efficient allocation of water in the next step depends on it. The collection of information can be the basis of a bidding process in which agents offer to buy water at a given price. In the case of irrigation agents, information such as crop area, crop type, yield, crop price and crop water requirement over a period can be used to determine the bid for each agent and, based on the bid information, the demand curve can be inferred using the residual imputation method (Pulido-Velazquez et al., 2008; Riegels et al., 2013). This method assumes that all input costs, except for the cost of water, are known. The water value is then imputed as the residual of the observed gross benefits after all non-water costs are subtracted (Young, 2005).

In order to control the declarations of agents in the agricultural sector, the RBA can use techniques such as remote sensing to validate land classification and cropping areas (Gallego et al., 2014; El-Kawy et al., 2011; Rozenstein and Karnieli, 2011). As an example, the European Union uses an Integrated Administration and Control System (IACS), which includes a land-parcel identification system (LPIS), to control declarations from farmers for financial aid grants (Oesterle and Hahn, 2004). The LPIS uses orthophotos to monitor the evolution of the land cover and the management of crops, and enables more accurate declarations by farmers.

In the case of hydropower, information regarding energy production and scheduling is important. For example, power plants might be offline for maintenance or might be obliged to generate a minimum amount of energy to meet their contractual commitments. Also, water use requirements such as environmental flow and minimum domestic use supply will be required.

The unconstrained or expected net benefits (ENB) for a water user are the consumer surplus (Fig. 1), which is the area under the demand curve above the price P_D. The surplus is the private user cost of water and corresponds to the willingness to pay for the last unit of water demanded in a situation where allocation is unconstrained. This area is made up of three regions (A, B and C) that will be discussed later.

2.2 Water allocation

Once water user information has been collected, allocation decisions are identified by matching demand with supply in a cost-efficient way, i.e., by giving priority of access to users with the highest productivity. In order to do this, an aggregation of the demand curve is carried out, which means that a distinction must be made between rival and non-rival water uses. When water users are not in competition for the same unit of water, non-rivalness is observed. For example, water flowing through a dam may be considered a non-rival water use since a unit of water released through one dam can be used downstream by another dam. In rival water use, units are consumed and are no longer available to other water users

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[2] One could also argue that a true market is created by assuming that every agent agrees with, and respects, having to pay for water.

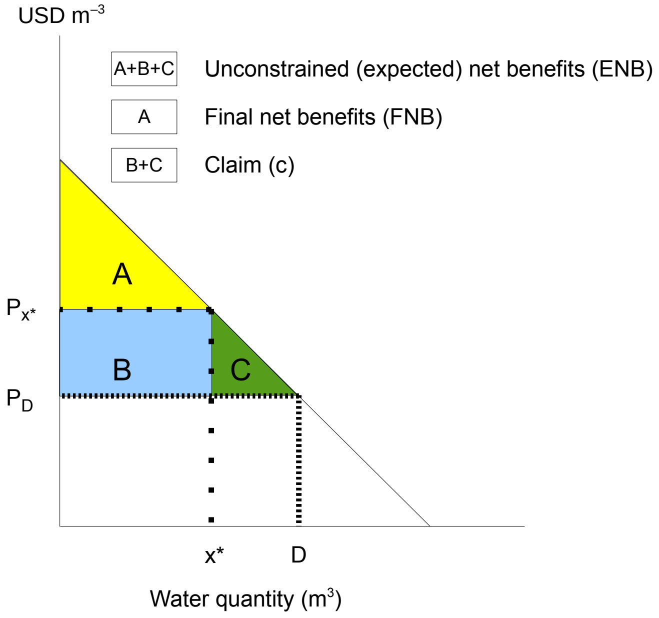

Figure 1. Demand curve. D: quantity of water demanded for a time period; x^*: quantity of water allocated for a time period; P: price of water.

(for example, water lost to irrigation or water held in a reservoir during a period when it is required downstream for irrigation). In this case, the demand curves are summed horizontally (see Fig. 2). Rival water uses need to be coordinated to prevent conflicts. The decision to divert one additional unit of water to any rival use depends on the at-source value[3] of water for that use. If this value is larger than the at-source value of all downstream marginal users, then it will be diverted to the rival use. See Tilmant and Kinzelbach (2012) for a detailed description of rival and non-rival water uses. The value of the last unit of water at any site, then, is the sum of the marginal values of the non-rival users since the demand curves can be summed up vertically (see Fig. 2). This aggregation of the demand curve is done automatically in hydro-economic models. Hydro-economic models, then, can be used to determine the allocation of water between users at the same site and over a basin (comprising a number of sites) and to determine the marginal value of water and economic benefits at each site. A description of the mathematical formulation involved is given in the Appendix.

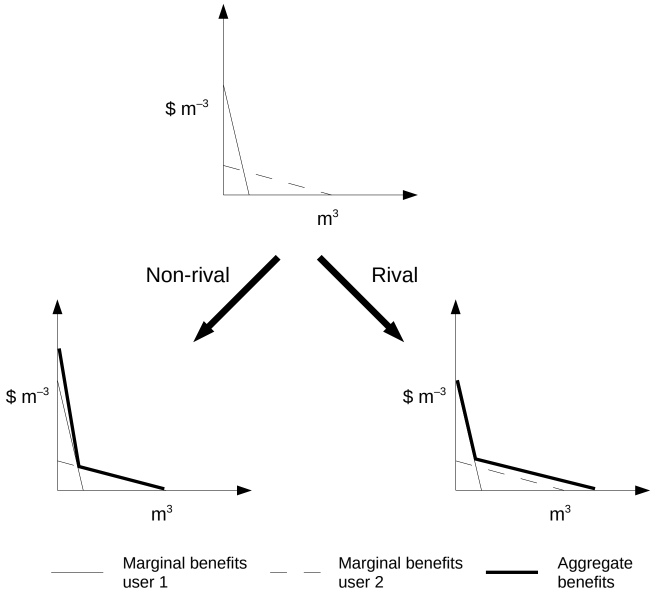

Figure 2. Aggregation of demand curves for rival and non-rival water uses for a given time period.

2.3 Collection of bulk water charges

Based on the water allocation decisions and the corresponding water fluxes, pseudo-market transactions occur between the RBA and the water users. Users must pay the RBA for the water allocated to them. The cost of water is the marginal water value or shadow price (λ) calculated by the hydro-economic model at the site of water abstraction or use. Economic theory indicates that for efficient water allocation to occur, the price that users pay for the resource must be equal to the marginal value of still available opportunities of water use, which reflects the social cost of using water at a particular site. If the user pays less than this, the resource is overconsumed or overutilized, as no efficient rationing occurs. Conversely, a user price higher than the marginal value would result in underconsumption/underutilization.

The RBA charges for the water entering the system in order to cover the costs associated with its mandates (conservation, coordination, compensation). In the case of consumptive users, water is purchased from the RBA at the marginal water value (the value of a marginal unit of water) at the site of abstraction. Non-consumptive users buy inflow from the RBA at a price equal to the difference between the marginal value of water at the user site and the marginal value of water at the downstream site (Fig. 3). This bulk water charge system is based on a dynamic water accounting framework presented by Tilmant et al. (2015).

Payment for bulk water use has been addressed, recently, by the United Nations in their 2014 World Water Development Report (United Nations World Water Assessment Programme, 2014) in which they state that economic instruments such as markets for buying and selling a resource (such

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[3] The at-source value of water is observed at the location where bulk water is diverted. The at-site value corresponds to the value of water delivered to the users (for example, a farm at the end of a conveyance and distribution system). At-site water values are generally larger than at-source values because they include losses in the system and conveyance costs. In the study of intersectoral allocation choices, at-source water values should be used (Young, 2005).

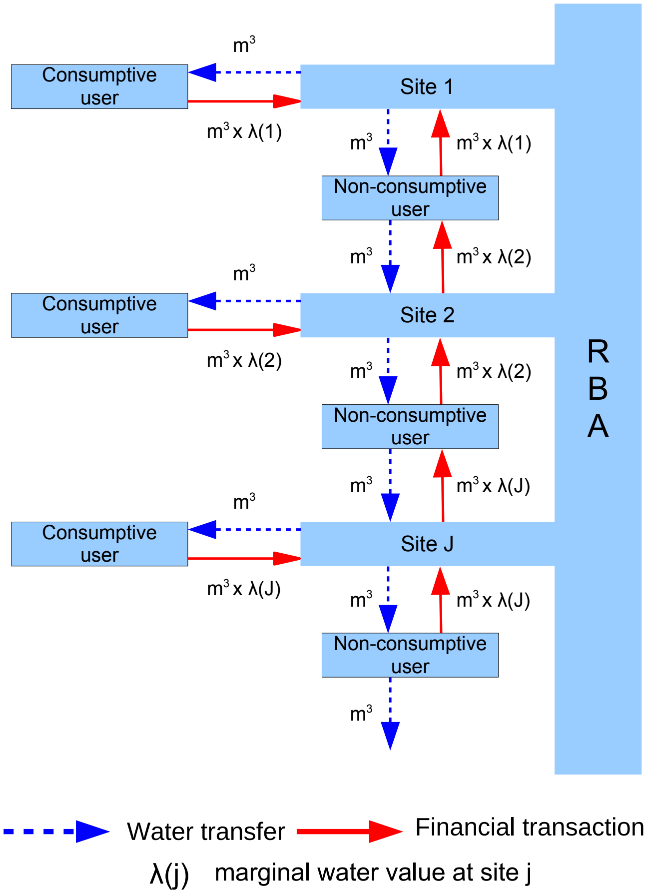

Figure 3. Collection of bulk water charges for a given time period.

as water) or the imposition of water use tariffs could create incentives for more efficient use. And, in fact, payment for bulk water supply has been established in recent water laws in Zimbabwe, Tanzania and Mozambique (The World Bank, 2008).

Once transactions are collected by the RBA, water costs (CW) for each water user can be calculated along with the final net benefits (FNB), which are equivalent to the consumer surplus shown, in Fig. 1, as the area above the line P_{x^*} (area A). Line P_{x^*} is the social cost of water where x^* is the economically efficient water allocation.

The difference between the benefits expected by each agent (ENB) and the final net benefits received (FNB) is the amount an agent will claim for compensation in the next step (c) and is equal to the value of the externalities (B+C in Fig. 1). These claims are composed of the difference in water costs between the unconstrained water demand (D) and the actual water allocation (x^*), which is area B in the figure, and the cost of cooperation (CC), which is the loss in benefits due to the allocation of fewer resources than what was demanded (area C in the figure).

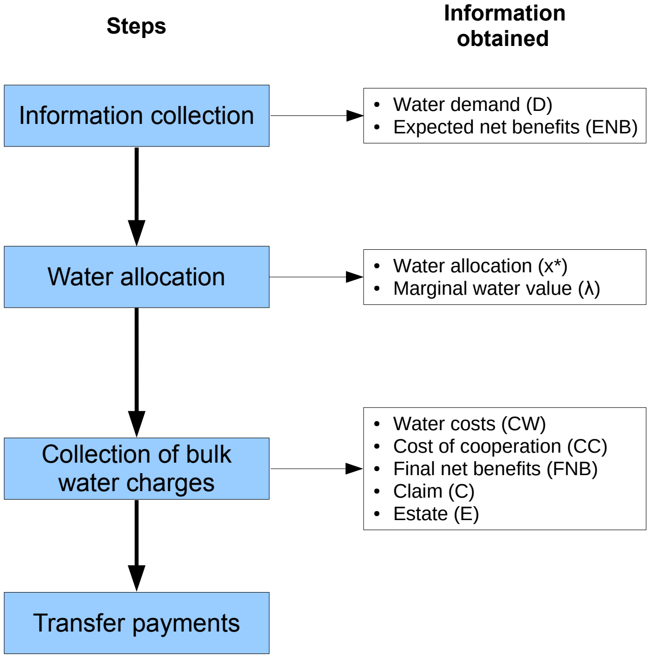

Figure 4. Flowchart of methodology including information obtained at each step.

2.4 Transfer payments

At this point in the methodology, the RBA has collected an amount of money, referred to as the *estate* (E), that can be shared among the water use agents. Using an axiomatic approach, a method of sharing this estate should be determined. The aim of the axiomatic approach is to find and capture the notion of fairness that water users could agree upon. The approach then sets out axioms (properties) that fairness should or should not satisfy. Finally, these properties are translated into a sharing rule that quantifies the particular definition of fairness. How the benefits are shared depends entirely on this definition as agreed to by water users. For example, a simple proportional sharing method may satisfy the properties of equity defined by the users, or an egalitarian method, or some other form of sharing may be required. Since each river basin will have a different definition of fairness (depending on conditions in the basin and the outcome of negotiations with the water users), each river basin will likely have its own unique sharing rule.

A flowchart of the complete methodology, including information obtained at each step, is shown in Fig. 4.

3 Case study

3.1 Eastern Nile River basin

The Eastern Nile River basin is used to illustrate the methodology described in the previous section. Covering an area of

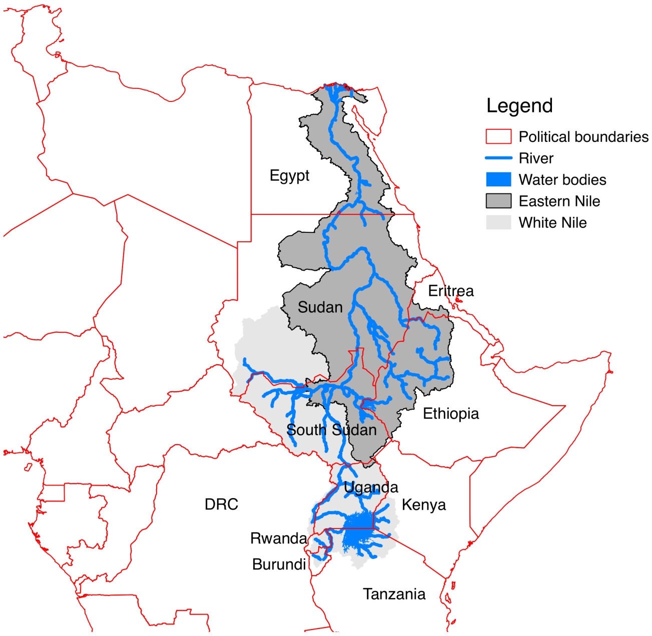

Figure 5. Eastern Nile River basin

approximately 330 000 km^2 and with a length of 1529 km, the Blue Nile originates in the highlands of Ethiopia and flows into Sudan, where it joins the White Nile at Khartoum to form the Main Nile. The Main Nile then flows out of Sudan, into Egypt, and discharges into the Mediterranean Sea. The Eastern Nile River basin is composed of the Blue Nile, the Tekeze-Atbara, the Baro-Aboko-Sobat, the White Nile downstream from Malakal and the Main Nile sub-basins (Fig. 5).

The dominant uses of water in the Eastern Nile River basin are irrigated agriculture and hydropower generation, mostly in Sudan and Egypt. This is, however, likely to change in the near future with the completion of the Grand Ethiopian Renaissance Dam on the border of Ethiopia and Sudan.

There is a long history of unsuccessful negotiations over water allocation and development of Nile water resources. Attempts at cooperation and benefit sharing within the Eastern Nile basin go back to the early part of the 20th century. The 1929 Nile Waters Agreement between Sudan and Egypt prioritized Egyptian water needs and reportedly gave Egypt the right to veto future hydroelectric projects along the Nile (Brunnée and Toope, 2003). Sudan and Egypt subsequently replaced the 1929 treaty, in 1959, with the Agreement for the Full Utilization of the Nile Waters, which essentially allocated the entire flow of the Nile at the Aswan Dam to Sudan and Egypt. Unsurprisingly, this has caused regional tension with the other riparians, who invoke the Nyerere Doctrine[4], and general principles of international water law, to contest the 1959 agreement and claim a share of the Nile waters.

In 1999 the Nile Basin Initiative (NBI) was undertaken with the goal being to adopt a comprehensive, permanent, legal and institutional agreement on the Nile River basin. So far there has been little success in negotiations leading to an agreement. However, a Cooperative Framework Agreement (CFA) was signed by a number of the Nile basin countries, with the notable exceptions of Egypt, Sudan and South Sudan.

Regional tensions have further complicated Nile cooperation efforts. For example, Ethiopia and Egypt have a long history of distrust and Egypt and Sudan, as well as Eritrea and Ethiopia, have long unresolved border disputes. Additionally, many Nile riparians have been broken by internal conflicts and instabilities that result in challenges to international relations.

In recent years, the construction of the Grand Ethiopian Renaissance Dam has been a source of concern and conflict among the three riparian countries. It should be noted, however, that in early 2015, Egypt, Sudan and Ethiopia signed an agreement on the declaration of principles with respect to the project.

It is pretty much agreed, at this point, that benefit sharing may offer a solution to the stalemate surrounding water use and allocation in the Eastern Nile River basin. While the concept of benefit sharing can be appreciated by most riparian countries, questions regarding methods of sharing benefits have emerged. The three Eastern Nile River basin countries need to, first and foremost, identify the bundle of benefits that can be generated, and then agree on a mechanism for sharing these (Tafesse, 2009)).

3.2 Information collection

Given the lack of accurate data with respect to irrigated agriculture in the Nile River basin, a net return of 0.05 USD m^{-3} is chosen as in Whittington et al. (2005). For hydropower it is assumed that each MWh generated has an economic value averaging 80 USD MWh^{-1} for firm power and 50 USD MWh^{-1} for secondary power. These values are consistent with feasibility studies of hydroelectric dams in Ethiopia. Using these values the unconstrained ENB are determined for each water use agent as

$$\mathrm{ENB}_j = D_j \cdot P_j, \tag{1}$$

where D_j is the unconstrained quantity of water demanded by agent j and P_j is its productivity. Note that the assumption is made that users do not currently pay for water.

The water demand for the irrigation agents is equal to the crop water demand. For the hydropower agents the water demand is equal to the amount that they are allocated in the next

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[4] The Nyerere Doctrine of state succession, founded by the first President of Tanzania, states that a new nation should not be bound to international agreements dating back to colonial times and that these agreements should be re-negotiated when a state becomes independent.

step. Since the allocation is economically efficient, the hydropower agents are assumed to be satisfied with the amount of water flowing through the turbines.

3.3 Water allocation

The stochastic multistage decision-making problem (Eqs. A1 to A4 defined in the Appendix) was solved using stochastic dual dynamic programming (SDDP). Details of this algorithm can be found in Goor et al. (2010) and in Tilmant and Kinzelbach (2012). The hydro-economic model of the Eastern Nile basin is based on the schematization shown in Fig. 6. In this study the assumption is made that the Grand Ethiopian Renaissance Dam (located at H8 in Fig. 6) is online. Allocation decisions are chosen to maximize expected net economic returns from irrigated agriculture and hydropower generation over a planning horizon of 10 years and for 30 hydrologic sequences (see Arjoon et al. (2014) for a description of the model).

Once the allocation decisions are determined, the actual gross benefits (GB) can be calculated as

$$\mathrm{GB}_j = x_j^* \cdot P_j, \tag{2}$$

where x_j^* is the water allocation decision for agent j. The difference between the ENB and GB is the cost of cooperation (CC) to the agent due to the efficient allocation of water. In other words, it is the difference between the amount of benefits the agent is expecting to get if their unconstrained water demand is met and the actual benefits the agent receives given the allocation decision, excluding water costs.

3.4 Collection of bulk water charges

The total of the transactions collected by the RBA (E), minus yearly operating expenses of 3 million USD, will be used to compensate the agents for a percentage of the benefits lost either through efficient allocation (cost of cooperation) or water costs. Operating expenses of 3 million USD yr^{-1} are in line with those published by power pools (Southern African Power Pool, 2009) and river commissions (Mekong River Commission, 2013).

Final net benefits for each agent can be calculated as

$$\mathrm{FNB}_j = \mathrm{GB}_j - \mathrm{CW}_j, \tag{3}$$

where CW_j is the cost of water for agent j.

3.5 Transfer payments

Once the final net benefits have been determined, transfer payments can be calculated for each agent. To do this, the total cost for each agent needs to be calculated, which will give the upper limit to the claim (c) of an agent to the estate.

Figure 7 shows the annual demand curve for an irrigation agent in this case study. In this study, we implicitly assume that the input demand is horizontal (perfectly elastic) with the price (P) = marginal productivity. The area to the left of line D (comprising areas A, B and C) is the ENB (we see that the agent does not pay for water) resulting from unconstrained water use. When water is constrained, area A is the FNB. The claims (c) are divided into two parts: area B is the cost of water (CW) to the agent and area C is the cost of cooperation (CC) due to the efficient allocation of water. Area B also represents the amount of money that the RBA collects from this agent. As previously mentioned, for hydropower agents the water demand and the water allocation are equal; therefore, there is no cost of cooperation. The claim (c), then, for a hydropower agent, is the cost of water (CW). Over the whole basin the amount that the RBA collects (and is available for

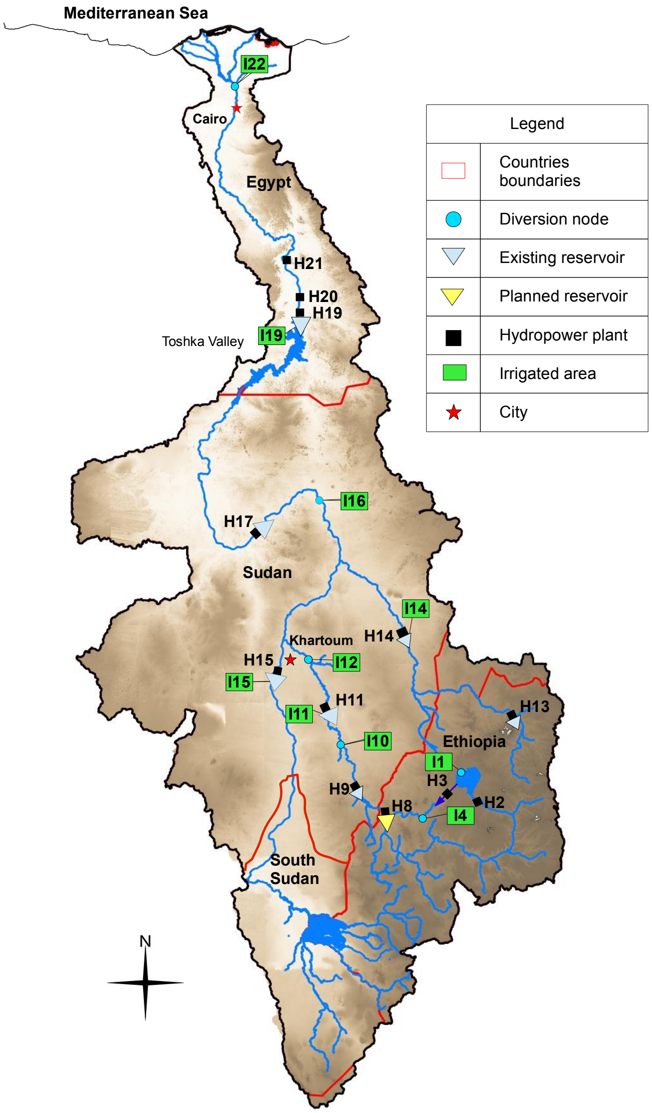

Figure 6. Model schematic of the Eastern Nile River basin. Irrigation agents (I) and hydropower agents (H) for this case study are shown. Note that the numbering is not consecutive because there are nodes that represent agents that are not part of the case study.

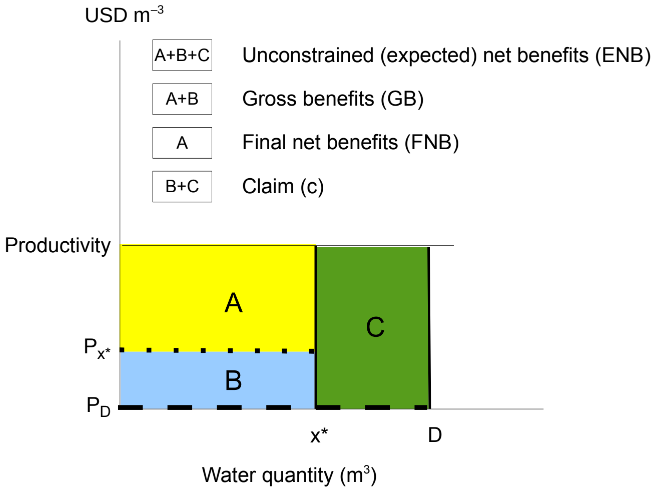

Figure 7. Demand curve for the case study. D: quantity of water demanded for a time period; x^*: quantity of water allocated for a time period; P: price of water.

transfer payments) is enough to reimburse the agents for the actual cost of water; however, as mentioned, USD 3 million are held back for annual operating expenses. Therefore the shortfall between the amount the RBA has to share and the claims of the agents is the total cost of cooperation for irrigation agents ($\sum \mathrm{CC}_j$) plus operating expenses.

The situation in which the amount available to share between agents is less than the total claims of the agents is, by definition, a bankruptcy problem.

In this case study, the collected benefits are shared among the water use agents following a rule that was developed based on a number of well-defined properties in the bankruptcy literature (*feasibility, non-negativity, claims-boundedness*) as well as some that are specific to the problem (*solidarity, security of minimum benefits*).

It should be noted that, for this study, the properties of this rule were not developed with stakeholder input, as this was beyond the scope of this research project. Although stakeholder involvement is imperative in this institutional arrangement, in this case study, we are giving an objective viewpoint, and this analysis serves as a benchmark or reference point.

Benefits are shared in such a way as to ensure that each agent has the same proportion of final costs ($\mathrm{ENB}_j - (\mathrm{FNB}_j + \mathrm{tp}_j)$) to benefits demanded ($\mathrm{ENB}_j$) (where tp_j is the monetary transfer payment made to the agent) and that these are minimized. By extension, this rule also ensures that each agent receives an equal proportion of final benefits ($\mathrm{FNB}_j + \mathrm{tp}_j$) to benefits demanded ($\mathrm{ENB}_j$) and that these are maximized. This rule also applies a *solidarity* property in which all agents take equal responsibility for the shortfall in benefits at certain nodes due to the efficient economic allocation of water over the basin, and a property of *security of minimum benefits* in which the benefits obtained from the use of water (FNB_j) are uncontested.

The compensation rule is defined as follows:

$$tp_j = \mathrm{ENB}_j - (\mathrm{FNB}_j + \gamma \mathrm{ENB}_j), \tag{4}$$

where γ is chosen such that

$$\sum tp_j \leq E. \tag{5}$$

Equation (5) ensures the property of *feasibility*, which is the requirement that the sum of the transfer payments not exceed the amount available to share.

The following constraints also apply:

$$tp_j \geq 0, \tag{6}$$

$$tp_j \leq c_j. \tag{7}$$

Equation (6) ensures *non-negativity*, which requires that each agent receive a non-negative amount, and Eq. (7) ensures *claims boundedness*, which requires that each agent receive, at most, the amount of its claim.

Rewriting Eq. (4) to read

$$\gamma = (\mathrm{ENB}_j - (\mathrm{FNB}_j + tp_j)) / \mathrm{ENB}_j \tag{8}$$

shows that the property of *solidarity* is supported by ensuring that the final cost ($\mathrm{ENB}_j - (\mathrm{FNB}_j + \mathrm{tp}_j)$) to expected benefit ($\mathrm{ENB}_j$) ratio for all agents is the same.

In this final step, the transfer payments are calculated and the total final benefits (FNB + tp) for each agent are determined.

4 Results

The analysis of results was carried out on year 4 of the 10-year planning horizon. This ensures a steady-state condition that is not influenced by initial hydrological and storage conditions or by any end-effect distortion due to reservoir depletion that occurs as the end of the planning period approaches (Arjoon et al., 2014). As previously explained, the amount of water allocated to hydropower agents is equal to the amount demanded. This means that all hydropower agents receive 100 % of the water demanded. The efficient allocation of water results in most irrigation agents also receiving their unconstrained demand. The exceptions are agents I1, I4 and I14, who receive, on average, 1, 0 and 94 % of their unconstrained demand, respectively (see Fig. 8). This result is not unexpected because, from an economic standpoint, irrigation in the Eastern Nile River basin should take place downstream after water has been used for hydropower generation upstream (Whittington et al., 2005). These three irrigation agents have cooperation costs as well as, possibly, water costs. Looking at the cumulative distribution of the proportion of the allocated amount of water to the amount received for these agents (Fig. 9), we see that 95 % of the time, agent I1 does not receive any water. Agent I14, on the other hand, receives its full demand about 75 % of the time.

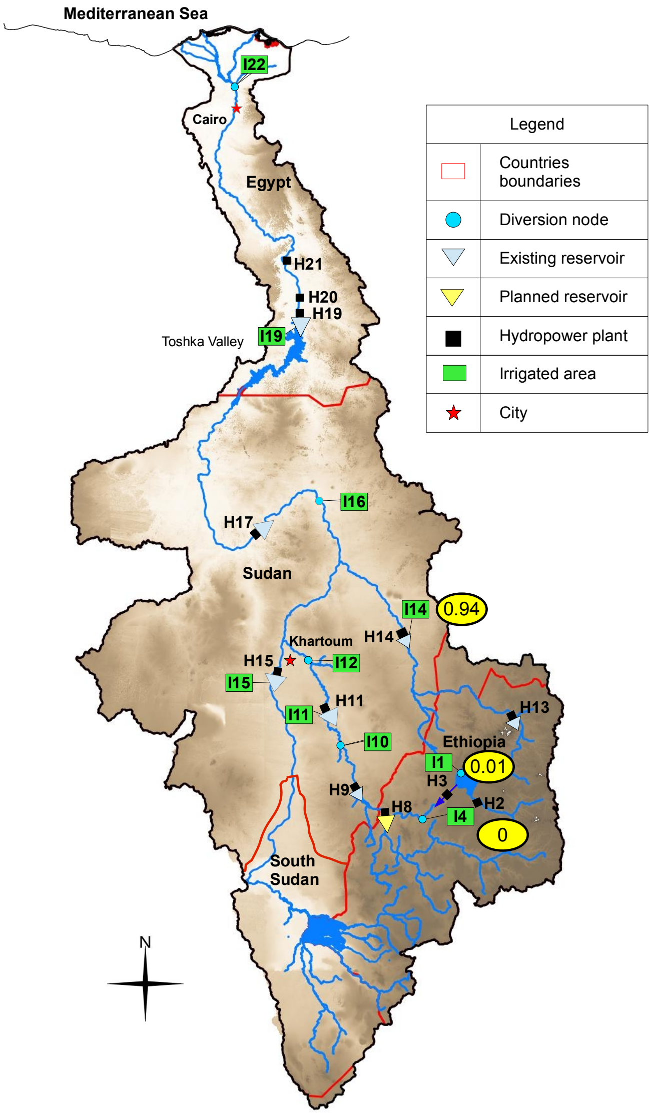

Figure 8. Average proportion of water allocation to unconstrained demand for all agents. Only the values for those agents in which the proportion is less than 1 are shown.

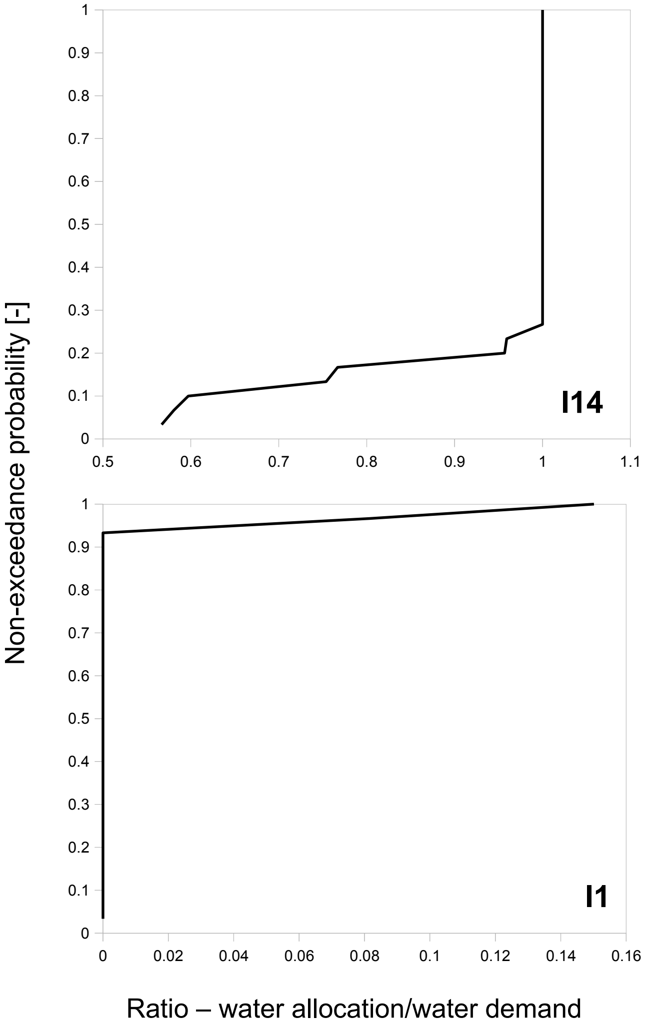

Figure 9. Cumulative distribution function for the proportion of water allocation to unconstrained demand for agents I1 and I14.

Agent I4 (not shown in Fig. 9) always receives 0 %. The rationing of water for upstream irrigation users is a result of the horizontal demand curve used for irrigation. If more detailed economic/agricultural data were available, a non-horizontal demand curve could be produced. This may result in irrigation schemes with high value crops having priority to water and those areas with low value crops not being irrigated. This means that the irrigation water users that are rationed may change and they may be more spread out over the basin.

Overall, the agents with the smallest claims are all hydropower agents in Sudan (H9, H11, H14, H15) with marginal values that are almost equal to marginal values at the downstream sites (see Fig. 10). This means that they sell water downstream at about the same price that they paid for it, resulting in lower water costs. Figure 11 gives a basin-wide view of the percentage of the unconstrained benefits claimed by each agent, by agent type, on average. The irrigation agents upstream claim a larger percentage of their expected benefits because, first, they pay more for water and, second, they also have cooperation costs. With respect to hydropower agents, H8 and H19 (Grand Renaissance and High Aswan, respectively) claim the largest percentage of their expected benefits. In both cases, the cost of water at these sites is much greater than the cost of water at the respective downstream sites.

From the collection of bulk water charges for the period analyzed (year 4), the RBA ends up with USD 3894 million to allocate between the agents (after subtracting USD 3 million for operating costs). The total claims amount for all agents, for the year, is USD 4266 million, which means that there is a shortfall of USD 372 million between the

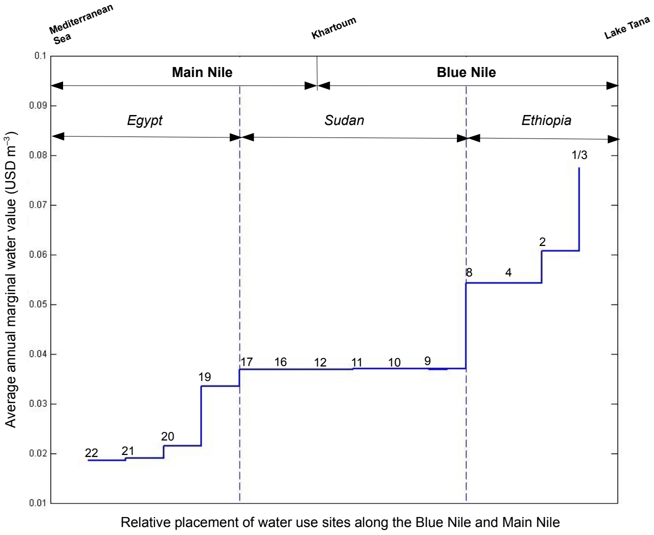

Figure 10. Marginal water value – Blue Nile and Main Nile

amount available to share and the claims, or about 9 % of the total claims.

Using the bankruptcy rule developed for this example, the average amount of transfer payment is calculated for each agent. The ratio of FNB to ENB, referred to as the *initial ratio*, and final net benefits plus transfer payments (FNB+tp) to ENB, referred to as the *final ratio*, are determined and analyzed. These results were analyzed over the 30 different hydrologic sequences to assess how this rule performs under varying hydrologic conditions.

Figure 12 shows the mean values for initial ratios (shown as large filled squares) and final ratios (shown as large filled diamonds) for irrigation agents as well as the values for each of the hydrologic sequences. Agents I1 and I4 receive little or no irrigation water, on average, as discussed previously. Agent I14 initially receives about 23 % of its expected net benefits, on average. This agent is located at the Kashm El Girba dam, on the Tekeze-Atbara River. The flow of this river is highly seasonal, with annual flows entering Sudan from Ethiopia restricted to the flood period of July to October. The design storage capacity of the reservoir at this site is about 10 % of the inflow; however, high sedimentation in the reservoir dropped the storage capacity by 50 % as of 1977. This loss of storage capacity has resulted in severe water shortages during drought years and an associated decline in the crop area cultivated. As a result, the restriction of water for this irrigation agent is more probably due to the hydrology as opposed to being economic in nature. Due to flow variation, the marginal water values are highly variable at this site, resulting in a wide spread of initial ratios over the hydrologic sequences (as indicated by a large vertical spread of data points on the graph for this agent). All other agents always receive their full unconstrained demand. Variability in the initial ratios of these agents is due to variability in the marginal water values over the hydrologic sequences.

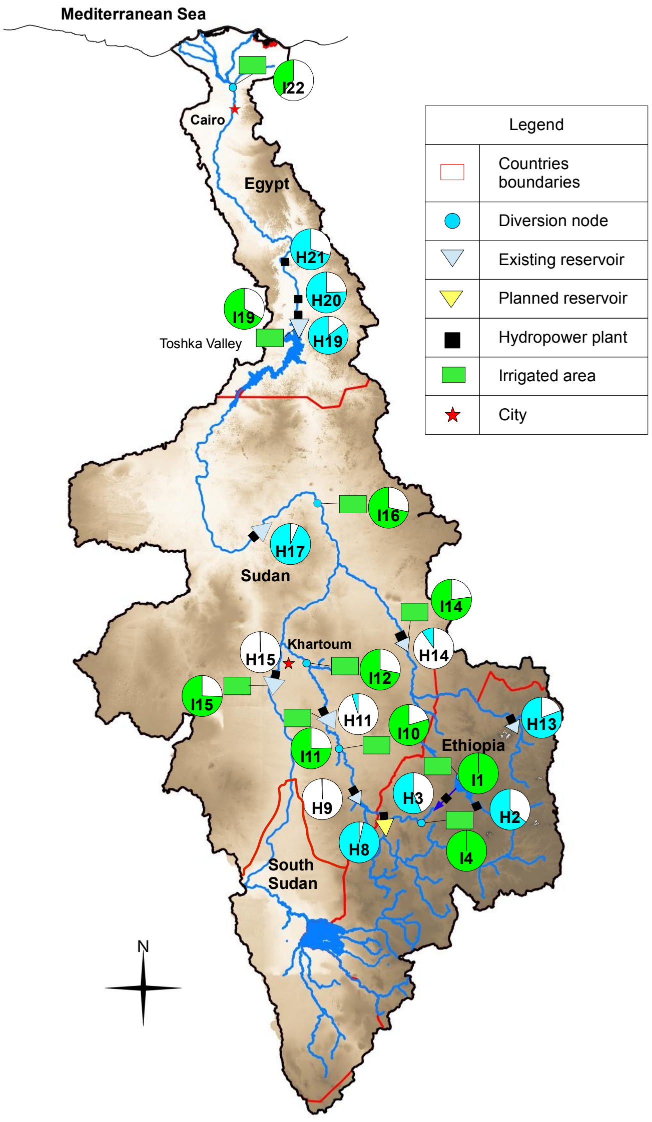

Figure 11. Percentage of unconstrained benefits claimed by agents.

Results for hydropower agents are shown in Fig. 13. Here we see more variation in the initial ratio than for the irrigation agents. The upstream hydropower agents (H2, H3), and those on the Tekeze-Atbara River (H13, H14), have large variations in initial ratios as a result of large inter- as well as intra-year variations in flow (and subsequently in marginal water values), which occurs because these sites are all upstream of flow regulating infrastructure. The agents with the smallest claims are the four smallest hydropower agents in Sudan (H9, H11, H14, H15). These agents have the largest initial ratios and, therefore, often do not receive monetary transfers. This also results in the final ratios for hydropower agents not being equal because the property of non-negativity, which is used to define the sharing rule, allows an agent to keep its initial

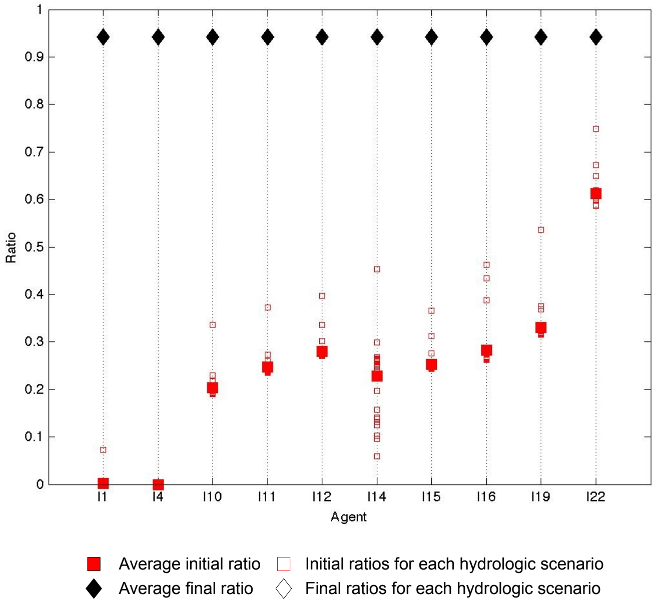

Figure 12. Initial and final ratios for irrigation agents.

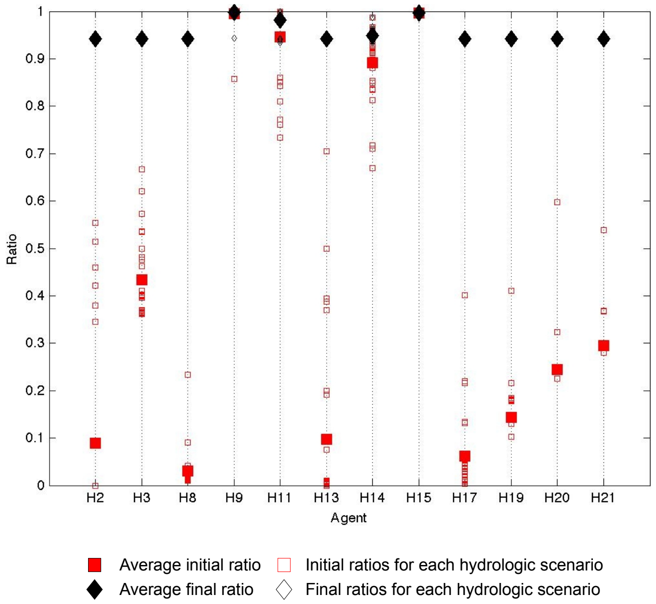

Figure 13. Initial and final ratios for hydropower agents.

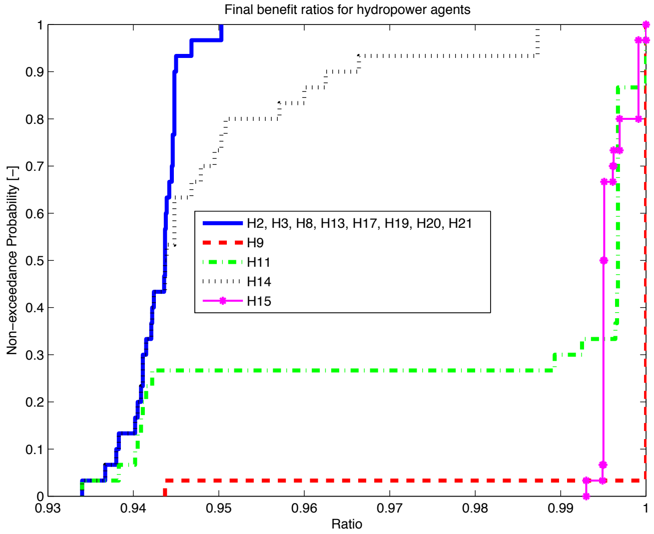

Figure 14. Final benefit ratio for hydropower agents.

benefits from water use even if this results in its final ratio being larger than those of the other agents.

Overall, the average final ratios for all agents (irrigation and hydropower) are equal, with the exception of agents H9, H11, H14 and H15, as mentioned above. There is also very little variation in final ratio values with respect to hydrologic sequence. The final ratio for irrigation agents varies from 93.5 to 95 % of their uncontested benefits. For hydropower agents the statistical distribution of final benefit ratios is shown in Fig. 14. We see that these final ratios also vary between 93.5 and 95 % with the exception, again, of agents H9, H11, H14 and H15, which have high initial ratios that vary with inter- and intra-annual variations in the marginal value of water. These results indicate that the sharing rule used is predictable in that agents can expect similar final benefits regardless of the hydrologic conditions.

Results that warrant a closer look are those for the upstream irrigation agents I1 and I4. We can conclude that, in this case study, given the economic information used in the model, it is economically inefficient to irrigate upstream in the basin regardless of the hydrologic sequence (meaning that even in situations of high flow years, there is no irrigation water allocated to these agents). However, these two irrigation agents consistently demand fairly substantial transfer payments even though they do not contribute economically to the basin. This becomes an obvious problem of fairness for the other agents. If these results persist over a number of years, the RBA could use this information for better management by ensuring that agriculture is developed downstream or that upstream agricultural sites have a high productivity value.

Finally, it should be noted that we make no attempt to compare the results of the case study with current water use in the basin. While the presented case study is hypothetical and is not consistent with the actual, current situation, it represents a possible long-term future scenario in the basin, and the results reflect these assumptions. In the case study, we assume complete cooperation; there is expanded irrigation in the basin and the Grand Ethiopian Renaissance Dam is online.

5 Conclusions

The sharing of benefits among agents in a transboundary river basin is based on three fundamental questions: (i) how can the benefits of water use be quantified and monetized, ii) what mechanism can be used to allocate benefits, and (iii) upon what criteria should the sharing of benefits be based to ensure efficiency and equitability. It should be noted that there is no unique response to these questions. In this paper, we propose one approach for distributing the benefits of cooperative management in a river basin system comprised of rival and non-rival uses. To illustrate the approach, we used the Eastern Nile River basin as a case study due to the important hydropower and agricultural sectors spread over three countries.

The methodology described in this paper is based on the welfare distribution for each agent being equal to the sum of its benefits from water use plus a monetary transfer. First, efficient water allocation is implemented through the application of a hydro-economic model in order to maximize the benefits in the river basin. Second, a charge for the use of water is established. The price that agents pay for the use of water is equal to the marginal value of water at the site at which the agent receives its allocation. The total of the water charges is equivalent to the overall value of water in the basin that is used in the sectors being studied. Finally, the total of the water charges are reallocated over the basin to ensure that all agents pay the same ratio of costs to benefits, using an axiomatic approach. The whole system is overseen by an RBA.

The two main goals of benefit sharing, efficiency and equitability, are the foundation of this methodology. The hydro-economic model results are the efficient water allocations for each agent. Efficiency is also inherent in the benefit-sharing rule used to implement the monetary transfers in that all of the available money is shared among the agents. The defined properties of fairness are embedded in the sharing rule through the axioms.

This methodology can be useful to policy-makers in that the solution is more likely to be perceived as equitable, resulting in water use agents being more open to cooperation. An additional advantage of this method is the predictability of the final results. These results, over varying hydrological sequences, are shown to be relatively constant.

The importance of this methodology is that it can be adopted for application in negotiations to cooperate in transboundary river basins. The methodology is flexible in that there is no set way to allocate the water over the basin. Any hydro-economic model (or another method) can be used as long as the amount of water allocated to each agent, as well as the marginal value of water for each agent, is available. Also, the development of the sharing rule can be based on stakeholder input and will depend on specific conditions in specific river basins.

One obvious constraint of this method is its dependence on the existence of a strong basin-wide authority to impose fees and that can enable negotiations between stakeholders for the development of a sharing rule. Allowing all stakeholders a place at the table might prove challenging, especially for large systems with diversified water use activities. In the irrigation sector, for instance, farmers could be represented by a water user association. For uses of water as a public good, such as for environmental flows, the representative could be the Ministry of Environment of the country of interest. For municipal uses, the system could be designed in such a way that a minimum amount of allocated water is guaranteed (a fixed constraint in the allocation system), while quantities beyond that minimum would be part of the pool for which municipalities would have to bid. Industrial and power companies are easier to handle. All users that can be rationed (mainly private water users) are allowed a place at the table for the purpose of defining fairness with respect to transfer payments. Another possibility is that the government (or at least a high level representative of the stakeholders) has the ultimate negotiation power, akin to negotiations on trade liberalizations. Clearly, different lobbies exist that would try to influence the government, implying, ultimately, some form of compensation (the analysis of which is outside the scope of this paper).

Another constraint is the availability of reliable data. Some information such as market prices, either national or international, can be observed and transportation costs can be estimated, allowing for an approximation of the mark-up that may accrue to farmers, for example. This paper describes a system in which it is assumed that there is cooperation over the whole basin and that water users have agreed to bid for water and to supply the information that is necessary to make the methodology work. Increasingly, the information required is becoming available through the use of remote sensing and monitoring of river basins.

Incentives for water users to cheat, with respect to the data they provide, will remain even if the river basin authority is able to audit the bids. For industrial uses, including hydropower generation, cheating might be more difficult because the market prices and production functions are often well characterized. The main challenge is to be found in the agricultural sector because (a) it is often the largest water use in a basin (and, hence, cheating might have serious basin-wide consequences), and (b) the heterogeneity in terms of cropping patterns and irrigation efficiency requires that significant data be collected and analyzed to audit the demands. We argue that the incentives to cheat might not be eliminated, but they can be suppressed, or at least kept within limits, through a robust monitoring system and a strong RBA to negotiate disputes. An example of how this has worked, with good success, is the Indus River basin. Zawahri (2009), in discussing the Permanent Indus Commission, states "The commission's ability to monitor development of the shared river system has permitted it to ease member states" fear of cheating and confirm the accuracy of all exchanged data. Finally, its conflict resolution mechanisms have permitted the commission to negotiate settlements to disputes and prevent defection from cooperation.

This paper adds to the analysis of the sharing of economic benefits in transboundary river basins by describing a methodology for efficient and equitable benefit sharing based on operating the river basin as a water pseudo-market with the advantages of resource use optimization, improved resource reliability and enhanced security of resource supply. Also, we impose specific axioms, based on a stakeholder vision of fairness, on the compensation scheme and derive a unique solution for the distribution of monetary payments. This technique may lead to a sharing solution that is more acceptable to shareholders because the definition of the sharing rule is not in question, as would be the case if we applied existing bankruptcy rules or other game theory solutions with their inherent definitions of fairness.

Appendix A

Hydro-economic modeling is a common tool used to analyze river basin systems and, specifically, water resources allocation problems. These models use a network representation of the system in order to physically connect various sources of supply with scarcity-sensitive water demands. Reviews of hydro-economic models can be found in Harou et al. (2009) and Brouwer and Hofkes (2008). Two classes of hydro-economic models exist: optimization-based and simulation-based. Both approaches have advantages and disadvantages, but the allocation decisions and the marginal costs of the binding constraints (the limiting resources or factors that prevent further improvement of the objective function) determined by an optimization model make this type of model attractive in the proposed methodology. In the system network, a water balance is evaluated at each node to determine the amount of water available for the demand sites connected to that node. The mass balance equation ensures that water is allocated to the connected water users to the extent permitted by water availability at the node. In the case of water scarcity, the marginal cost associated with the water balance indicates the shadow price of water or what the users would be willing to pay for an additional unit of water (Young, 2005).

In a hydro-economic water resource optimization problem, the objective function Z to be maximized includes the economic net benefits across all water uses over a given planning period.

$$Z^* = \max_{x_t} \left\{ \underset{q_t}{\mathbf{E}} \left[\sum_{t}^{T} \alpha_t b_t(\boldsymbol{w}_t, \mathbf{x}_t) + \alpha_{T+1} \nu(\boldsymbol{w}_{T+1}) \right] \right\}, \tag{A1}$$

where b_t are the basin-wide net benefits at time t, $\boldsymbol{x}_t$ the vector of allocation decisions, $\boldsymbol{w}_t$ the vector of state variables, α a discount factor, ν a terminal value function, $\mathbf{E}$ the expectation operator capturing he uncertainty that governs the hydrologic inflow q_t and Z the total benefit associated with the optimal allocations (x_1^*, x_2^*, ..., x_T^*).

This function is maximized to the extent permitted by physical, institutional or economic constraints:

$$g_{t+1}(\boldsymbol{x}_{t+1}) \leq 0, \tag{A2}$$

$$h_{t+1}(\boldsymbol{w}_{t+1}) \leq 0, \tag{A3}$$

$$\boldsymbol{w}_{t+1} = f_t(\boldsymbol{w}_t, \boldsymbol{x}_t, \boldsymbol{q}_t), \tag{A4}$$

where g is a set of functions constraining the allocation decision, h a set of functions constraining the state of the system and f a set of functions describing the transition of the system from time t to time $t+1$.

Included in the functions in Eq. (A4) are the mass balance equations for the river basin:

$$s_{t+1} - \mathbf{R}(r_t + l_t) - \mathbf{I}(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t, \tag{A5}$$

where s_t is the storage at time t, r_t the controlled outflows, l_t the uncontrolled outflows, i_t the water withdrawals, $\mathbf{R}$ and $\mathbf{I}$ the connectivity matrices representing the topology of the system (including return flows), and e_t the evaporation losses.

At the optimal solution of the problem (Eqs. A1 to A4), the solver provides the allocation decisions (x_1^*, x_2^*,..., x_T^*) and the marginal values of water (shadow prices) (λ_1, λ_2,...,λ_T) of the constraints. For the constrains in Eq. (A4), the shadow prices correspond to the marginal resource opportunity cost at the sites where water balances are computed.

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III

Bankruptcy Rules and Benefit Sharing in Transboundary River Basins

Diane Arjoon and Amaury Tilmant

In Preparation

2016

La coopération dans les bassins fluviaux transfrontaliers peut favoriser une répartition de l'eau économiquement efficace en permettant l'utilisation de l'eau où la productivité est la plus élevée. Cependant, si l'eau est entièrement allouée, ceci peut rationner certaines utilisateurs qui seraient moins coopératifs, à moins d'être indemnisés pour les avantages perdus de laisser couler l'eau en aval. Les utilisateurs rationnés auraient à payer un *coût de coopération*, lequel peut être défini comme la valeur monétaire des avantages perdus suite à l'application des politiques d'allocation à l'échelle du bassin. Dans une étude précédente, les auteurs définissent un arrangement institutionnel qui distribue les bénéfices dans un bassin fluvial transfrontalier en maximisant d'abord les avantages économiques de l'utilisation de l'eau et, par la suite, le partage équitable de ces bénéfices. Les méthodes d'analyse, en particulier celles concernant la répartition des actifs lors de faillite, ont été utilisés pour concevoir une règle de partage équitable des coûts de coopération. Dans cet article, nous évaluons les résultats des paiements de transfert en comparant la règle de partage développée par les auteurs (ECO) aux trois règles communes de partage utilisées lors de faillites (PRO, CEA, CEL) et expliquons pourquoi la règle ECO peut être plus équitable dans l'étude de cas du bassin oriental du Nil. Les résultats démontrent que la règle ECO attribue pour chacun des utilisateurs des paiements en proportion égale au rapport coût/bénéfices nets attendus. La règle ECO est basée sur certains paramètres définissant un partage équitable des bénéfices dans le bassin oriental du Nil. Cependant, la notion d'équité peut être différente dans d'autres bassins. En reconnaissant cette différence, les règles de partage s'appliquant à un bassin fluvial spécifique doivent être définies. Les méthodes de répartition des actifs utilisées lors de faillite, compte tenu de leur relative simplicité et flexibilité, peuvent s'avérer des outils utiles pour aborder cette problématique.

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Bankruptcy rules and benefit sharing in transboundary river basins

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Abstract Full cooperation in transboundary river basins can lead to economically efficient water allocation by allowing water to be used where productivity is the highest. However, if water is over- allocated, this can lead to some users being rationed, who would not agree to cooperate unless they are compensated for the benefits they lose by allowing water to flow downstream. Water users that are rationed are said to have a *cost of cooperation* which can be defined as the monetary value of benefits lost due to the application of basin-wide efficient allocation policies. In a previous study, the authors defined an institutional arrangement that distributes welfare in a transboundary river basin by first maximizing the economic benefits of water use and then equitably sharing these benefits. Analytical methods, specifically bankruptcy methods, were used to design a rule to equitably share the costs of cooperation through transfer payments to the water users. In this paper, we compare the results of transfer payments using the sharing rule developed by the authors (ECO) with the results that are obtained using three common bankruptcy sharing rules (PRO, CEA, CEL). The results show that the ECO rule allocates transfer payments in such a way as to equalize the proportion of cost to expected net benefits that the agents pay. The ECO rule is based on certain properties that may define equity in the sharing of benefits in the Eastern Nile River basin, however, equity considerations may be different in other basins. In acknowledging the differences in the notion of equity in different basins, sharing rules that apply properties specific to a river basin need to be defined. Bankruptcy methods, with their relative simplicity and flexibility, show promise as useful tools to approach these types of problems.

Keywords Benefit sharing · Bankruptcy rules

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1 Introduction

Full cooperation in transboundary river basins can lead to economically efficient water allocation by allowing water to be used where productivity is the highest. This allows for the maximization of economic benefits over the whole river basin, but also means that some water users will be rationed during years when water is fully allocated. These rationed users are often the consumptive water users located upstream in the basin (Ding et al, 2016; Tilmant et al, 2009).

Users that are rationed would not agree to cooperate unless they are compensated for the benefits they lose by allowing water to flow downstream. If upstream consumptive users do not cooperate, downstream users may experience decreased volumes of water flowing in the river (and decreased water quality through polluted return flows) so there is incentive for downstream users to ensure compensation to rationed users upstream.

Water users that are rationed are said to have a *cost of cooperation* which can be defined as the monetary value of benefits lost to rationed water users due to the application of basin-wide efficient allocation policies (Arjoon et al, 2016). This is not the same as the cost of non-cooperation described in Tilmant and Kinzelbach (2012) and Hu et al (2016) as the benefits lost over the entire basin as a result of the unregulated use of water or the inefficient assignment of water use rights. The cost of cooperation is specific to the users in a river basin that are rationed to ensure the maximization of total benefits over the basin. The cost of non-cooperation, on the other hand, affects downstream water users and results in economically inefficient welfare over the basin. How the burden of the cost of cooperation is shared among users in the river basin can be important in determining whether or not agents will agree to cooperate.

There are few studies found in the current literature that concentrate on defining and sharing the cost of cooperation, although some recent research is starting to focus on determining and sharing the benefits of cooperative water allocation in transboundary rivers. Jalilov et al (2015) present a number of scenarios to illustrate how the benefit sharing concept can be used to investigate water-energy-agriculture linkages in the Amu Darya basin. The authors quantify the basin-wide economic benefits for different operating scenarios of the Rogun hydropower plant and then discuss possible benefit sharing arrangements, with different forms of compensation, that could be used to facilitate cooperation between the riparians. However, no actual methods of compensation are investigated. Tilmant et al (2009) presents a methodology to derive the contributions of downstream non-consumptive hydropower water users to the financial compensation of upstream irrigation users who forego individual benefits so that social benefits can be maximized in the Euphrates River Basin. Ding et al (2016) develops a parallel evolutionary search algorithm to introduce a mechanism to re-distribute a central planner revenue among competing agents based on their contribution to the central solution, thereby maintaining efficiency and introducing equity through fairly allocated revenues for each water user. Wang et al (2008) present a cooperative water allocation model which, first, calculates initial water rights allocation and, then, pursues the optimal economic use of water through fair reallocation of water and the associated net benefits.

In a previous study, Arjoon et al (2016) define an institutional arrangement that distributes welfare in a transboundary river basin by maximizing the economic benefits of water use and then sharing these benefits in an equitable manner. Although the methodology described by Tilmant et al (2009) is similar to that of Arjoon et al (2016), there are a number of important differences. In Tilmant et al (2009) there are no water costs. The benefits that are used to compensate the rationed users are the additional benefits obtained by dynamic reallocation of the water resources. In Arjoon et al (2016), all water users are responsible for covering the shortfall in benefits to rationed irrigation users and all users must pay for water to cover the mandate of the river basin authority (RBA). In Tilmant et al (2009), although the assumption is made that the river basin is managed by an RBA, this RBA is ”imaginary” and the costs of its mandate are not considered in the system. Arjoon et al (2016) also discuss the dual of sharing these benefits which is the sharing of the cost of cooperation. Analytical methods, specifically bankruptcy methods, are used to design a rule to compensate rationed users and to ensure that the benefits of cooperation, and conversely the costs of cooperation, are equitably shared.

Analytical methods may be practical in operationalizing the concept of equity in the sharing of benefits in specific cases, with equity being seen as the key to successful benefit and cost sharing in international river basins. One of the analytical methods that has been studied for conflict management in resource allocation problems is bankruptcy theory. A bankruptcy situation arises when an asset (also called the estate) is to be distributed among a group of creditors where the value of the asset is insufficient to satisfy the total claims of the creditors to the asset (Herrero and Villar, 2001). Many rules have been developed to allocate the estate in a bankruptcy situation, with some of these rules being based on the associated cooperative bankruptcy game (Borm et al, 2011). The simplest and, thus, most widely used rules are: the proportional rule (PRO) which awards, to all creditors, an equal proportion of their claims; the constrained equal losses rule (CEL) which allocates, equally, the difference between the total claims of the creditors and the award available to share; and the constrained equal awards rule (CEA) which equally allocates the total estate available to share. Details of these bankruptcy rules, as well as many others, are documented by Thomson (2003).

Recently the three common bankruptcy rules (PRO, CEA, CEL) have been studied for the equitable sharing of water (Mianabadi et al, 2015; Madani et al, 2014; Mianabadi et al, 2014; Ansink and Weikard, 2012). In all of these examples, the authors acknowledge that a bankruptcy river water sharing system problem differs from an ordinary bankruptcy problem. In ordinary bankruptcy problems, claimants are characterized only by their claim to the estate. In a river allocation problem, where claimants are ordered linearly along the river, the agent's position in the order of agents, as well as their claims to the resources, play important roles in the solution (Ansink and Weikard, 2012). As well, in the case of transboundary river basins, the amount of flow that originates in a basin state can be considered as the contribution of the claimant to the estate (Mianabadi et al, 2014) and may be important in determining how much of their claim the agents expect to receive. Conventional methods such as PRO, CEA and CEL do not consider these aspects of the river sharing problem. In each of the above studies, sharing rules which extend conventional bankruptcy rules, to include these differences, are developed. Similarly, Madani et al (2014) develop a new bankruptcy-based mechanism to allocate water which provides solutions with respect to the temporal and spatial variability of water flow in transboundary river systems.

Bankruptcy rules may also be used to determine how the benefits of water use should be shared over a river basin. First, the amount of benefits available to share is less than the amount claimed by the water users, making this a true bankruptcy situation. Second, bankruptcy rules have relatively simple mathematical formulations and can easily be used by policy makers and easily understood by water users (Ansink and Weikard, 2012). The PRO, CEA and CEL rules, specifically, have strong theoretical and empirical support (Ansink and Marchiori, 2009) and a long history of practical and widespread use (Young, 1995). More pragmatically, these three rules define proportional sharing (PRO) and equal sharing (CEA, CEL) which are techniques that are often used to solve disputes in water management. For example, proportional sharing is used to address water conflicts in the Lake Urmia basin (Oftadeh et al, 2016) and in the Murry-Darling basin (Garrick, 2015). Finally, bankruptcy theory, which is a form of cooperative game theory, may provide solutions that are more useful than conventional cooperative game solutions when the information about the utilities of the stakeholders cannot be calculated or may not be accepted by all claimants (Zarezadeh et al, 2012; Madani and Zarezadeh, 2012).

The development of a new bankruptcy-based mechanism to share the benefits/costs of cooperation is presented by Arjoon et al (2016). In their methodology, agents are allocated water to ensure the economic efficiency of the river system, the agents pay for the water they are allocated, and the sum of these payments is then used to provide transfer payments back to the agents to ensure equitability. The final benefits of the agents are made up of two components: 1) the benefits that they receive through the use of the water allocated to them, and 2) the amount of the transfer payment that they receive. The new bankruptcy sharing rule takes the claim of the agents into account, but also the value of the benefits received through the use of water.

In this paper we compare the results of transfer payments calculated using the sharing rule developed by Arjoon et al (2016) (referred to as the ECO rule because the method is based on the sharing of benefits that are generated from the economically efficient allocation of water) with the results that are obtained using the three common bankruptcy sharing rules (PRO, CEA, CEL) and discuss why the ECO rule may be more equitable in the sharing of cooperation costs when the river basin is centrally managed.

In the next section, the Eastern Nile River basin case study is introduced and the hydro-economic model used to determine the efficient water allocation in the study by Arjoon et al (2016) is briefly described. The new ECO sharing rule is then described in detail, along with the three traditional bankruptcy rules (PRO, CEA, CEL). In section 3 the results of applying the 4 rules to the Eastern Nile Basin case study are analyzed and discussed. Section 4 summarizes the conclusions of the paper.

2 Methodology

2.1 Description of the case study

The Eastern Nile River basin is used to illustrate the methodology presented by Arjoon et al (2016). The basin covers an area of approximately 330 000 km^2. The Blue Nile, with a length of 1529 km, originates in the highlands of Ethiopia and flows into Sudan, where it joins the White Nile, at Khartoum, to form the Main Nile. The Main Nile then flows out of Sudan, into Egypt, and discharges into the Mediterranean Sea. The Eastern Nile River basin is composed of 5 sub-basins: the Blue Nile, the Tekeze-Atbara, the Baro-Aboko-Sobat, the White Nile downstream from Malakal and the Main Nile.

Irrigated agriculture and hydropower generation, mainly in Sudan and Egypt, are the dominant uses of water in the Eastern Nile River basin, although this is likely to change in the near future when construction of the Grand Ethiopian Renaissance Dam, on the border of Ethiopia and Sudan, is completed (completion is scheduled for 2017).

There is a long history of unsuccessful negotiations over water allocation and development of water resources in the Nile basin. In the 1929 Nile Waters Agreement between Sudan and Egypt, Egyptian water needs were prioritized and Egypt was given the right to veto future hydroelectric projects along the Nile. Sudan and Egypt subsequently replaced the 1929 treaty, in 1959, with the Agreement for the Full Utilization of the Nile Waters, which essentially allocated the entire flow of the Nile, at the Aswan Dam, to Sudan and Egypt. This has since caused regional tension with the other riparians, who invoke the Nyerere Doctrine, and general principles of international water law, to contest the agreement and to claim a share of the Nile waters.

Other regional tensions have further complicated Nile cooperation efforts. Ethiopia and Egypt have a long history of distrust and Egypt and Sudan, as well as Eritrea and Ethiopia, have long unresolved border disputes. Additionally, Nile riparians, such as Sudan and South Sudan, have been broken by internal conflicts and instabilities that result in challenges to international relations.

The construction of the Grand Ethiopian Renaissance Dam has also been a source of concern and conflict among the three riparian countries of the Eastern Nile River basin. However, in early 2015, Egypt, Sudan and Ethiopia signed an agreement on the declaration of principles with respect to the project and, at the end of 2015, it was announced that the three countries had reached a consensus to put the provisions of the declaration into practice by agreeing to the hiring of consulting firms that would conduct impact studies on the dam.

There is a general agreement that benefit sharing may offer a solution to the stalemate surrounding water use and allocation in the Eastern Nile River basin.

2.2 Hydro-economic model

In order to determine the efficient allocation of water in the Eastern Nile River basin, Arjoon et al (2016) applied a hydro-economic model.

Hydro-economic modelling is a common tool used to analyze river basin systems and, specifically, water resources allocation problems. These models use a network representation of the system in order to physically connect various sources of supply with scarcity-sensitive water demands. Two classes of hydro-economic models exist: optimization-based and simulation-based. Both approaches have advantages and disadvantages, but the allocation decisions and the marginal costs of the binding constraints (the limiting resources or factors that prevent further improvement of the objective function) determined by an optimization model make this type of model attractive in the proposed methodology. In the system network, a water balance is evaluated at each node to determine the amount of water available for the demand sites connected to that node. The mass balance equation ensures that water is allocated to the connected water users to the extent permitted by water availability at the node. In the case of water scarcity, the marginal cost associated with the water balance indicates the shadow price of water or what the users would be willing to pay for an additional unit of water.

In a hydro-economic water resource optimization problem, the objective function to be maximized includes the economic net benefits across all water uses over a given planning period.

$$Z^* = \max_{x_t} \left\{ \mathop{\mathbb{E}}_{q_t} \left[\sum_t^T \alpha_t b_t(\mathbf{w}_t, \mathbf{x}_t) + \alpha_{T+1} \nu(\mathbf{w}_{T+1}) \right] \right\} \tag{1}$$

where b_t is the basin-wide net benefits at time t, x_t is the vector of allocation decisions, w_t is the vector of state variables, α is a discount factor, ν is a terminal value function, $\mathbb{E}$ is the expectation operator capturing he uncertainty that governs the hydrologic inflow q_t and Z is the total benefit associated with the optimal allocations $(x_1^*, x_2^*, ..., x_T^*)$.

This function is maximized to the extent permitted by physical, institutional or economic constraints :

$$g_{t+1}(\mathbf{x}_{t+1}) \leq 0 \tag{2}$$

$$h_{t+1}(\mathbf{w}_{t+1}) \leq 0 \tag{3}$$

$$\mathbf{w}_{t+1} = f_t(\mathbf{w}_t, \mathbf{x}_t, \mathbf{q}_t) \tag{4}$$

where g is a set of functions constraining the allocation decision, h is a set of functions constraining the state of the system and f is a set of functions describing the transition of the system from time t to time $t+1$.

Included in the functions in equation (4) are the mass balance equations for the river basin :

$$s_{t+1} - R(r_t + l_t) - I(i_t) + e_t(s_t, s_{t+1}) = s_t + q_t \tag{5}$$

where s_t is the storage at time t, r_t is the controlled outflows, l_t is the uncontrolled outflows, i_t is the water withdrawals, R and I are the connectivity matrices representing the topology of the system (including return flows), and e_t is the evaporation losses.

At the optimal solution of the problem (equations (1) to (4)), the solver provides the allocation decisions (x_1^*, x_2^*, ..., x_T^*) and the marginal values of water (shadow prices) (λ_1, λ_2, ..., λ_T) of the constraints. For the constraints in equation (4), the shadow prices correspond to the marginal resource opportunity cost at the sites where water balances are computed.

The hydro-economic model of the Eastern Nile basin is based on the schematization shown in Figure 1. The allocation decisions are chosen to maximize expected net economic returns from irrigated agriculture and hydropower generation over a planning horizon of 10 years and for 30 different hydrologic scenarios. The assumption is made that countries cooperate in order to maximize basin-wide benefits.

2.3 The institutional arrangement

The institutional arrangement defined in Arjoon et al (2016) is made up of 4 steps (Figure 2). The arrangement is overseen by a river basin authority (RBA) who plays the role of water system operator. The mandate of the RBA consists of collecting information on water use and productivity; ensuring the efficient allocation of water between the different agents in the system; preserving the hydrologic integrity of the river basin; and coordinating the collection and redistribution of the benefits associated with the optimal allocation policies.

In the general methodology presented by Arjoon et al (2016), water users in a river basin bid for the amount of water they require or supply data so that their demand curve can be derived. A hydro-economic model is then used to determine the efficient allocation of water over the basin and the marginal value of water at each user site, with the main assumption being that there is total cooperation between the water users. In the methodology, water users must pay for the water they receive. The payment for water use, by all agents, is collected, and the total is redistributed back to the users in an equitable manner using a sharing rule developed specifically for this case study. A schematic of the methodology and the variables that define the problem at each step is shown in Figure 2:

- D is the water demand (m^3) for the agent;
- *ENB* is the expected net benefits (US dollars (USD)) which is equal to the amount of benefits the water user expects to receive if allocated its full demand and there is no cost for the use of water;

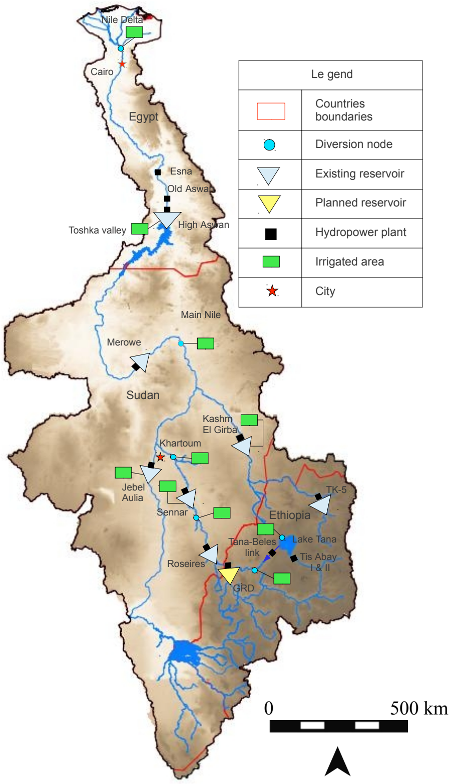

Fig. 1 Schematisation of the Eastern Nile River basin (from Arjoon et al (2014)).

- $x*$ is the amount of water actually allocated to the user (m^3) as determined by the hydro-economic model;
- λ is the marginal water value at the source of abstraction (USD/m^3) determined by the hydro-economic model;
- GB is the gross benefits (USD) an agent receives given the amount of water allocated to it;
- CW is the cost of water to the agent (USD);
- CC is the cost of cooperation (USD) which is equal to $ENB - GB$. The cost of cooperation is the loss in benefits to the agent as a result of receiving less water than demanded;
- FNB is the final net benefits to the user (USD) and is equal to $GB - CW$;
- C is the claim for the agent (USD) which is equal to $CW + CC$. This is the difference between ENB and FNB;

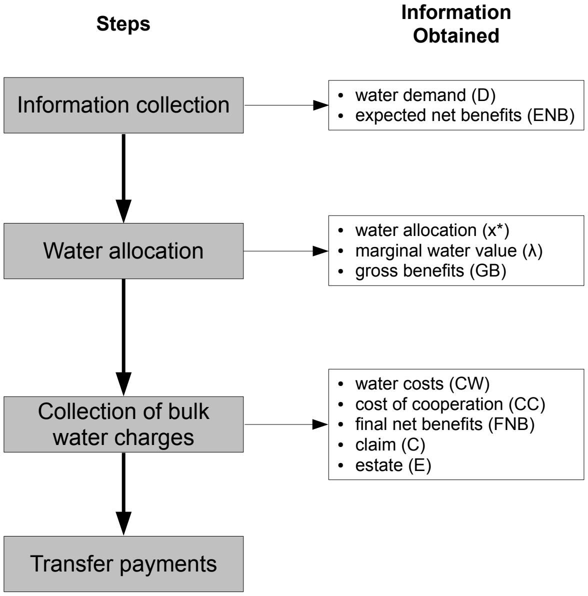

Fig. 2 Methodology and variables defined at each step (adapted from Arjoon et al (2016)).

- E is the estate available to share (USD) and is equal to $\sum_{j=1}^{J} CW_j$ minus an amount which is the cost of administering the overall system by the RBA. In their study, Arjoon et al (2016) sets this amount at 3 million USD.

2.4 Bankruptcy rules

In this paper, transfer payments calculated using the sharing rule developed by Arjoon et al (2016) are compared to those obtained using three common bankruptcy sharing rules.

In typical bankruptcy problems three variables are defined: (1) a finite set of agents or claimants J where $J = 1,2,..j$, (2) an estate E to be divided among the agents, and (3) the claim of each agent (C_j). In this simple bankruptcy situation, the claimants are characterized by their claims alone and the allocation of E to each agent is $F(J,E,C_j) = b_j$ where $b_j >= 0$.

The allocation of benefits to each claimant is defined, as follows, for each of the common bankruptcy rules applied in this study:

The proportional rule (PRO):

$$b_j^{PRO} = \gamma * C_j \tag{6}$$

where $\gamma = E/sumC$ and $\sum_{j=1}^{J} b_j^{PRO} = E$. When this sharing rule is applied to the institutional arrangement, each agent receives the same proportion of its claim.

The constrained equal award rule (CEA):

$$b_j^{CEA} = min(\beta, C_j) \tag{7}$$

where $\sum_{j=1}^{J} b_j^{CEA} = E$. The CEA rule assigns each agent an equal share (β) of the estate under the constraint that no agent receives more than his or her claim.

The constrained equal award rule (CEL):

$$b_j^{CEL} = max(0, C_j - \beta) \tag{8}$$

where $\sum_{j=1}^{J} b_j^{CEL} = E$ and β is the share of E allocated to the agent. Each agent receives a share of the estate such that their losses, in comparison with their claims, are equal under the constraint that no agent receives a negative amount.

The ECO rule:

As mentioned previously, the total benefits to the water user is made up of two components: the amount of benefits received through the use of allocated water (FNB_j) and the amount that the water user receives, as a transfer payment, from the estate (b_j). Arjoon et al (2016) proposed a new sharing rule, based on the principle that each user should receive the same proportion of total benefits to requested benefits ($(FNB_j + b_j^{ECO})/ENB_j$) or, conversely, that each user should pay the same percentage of expected net benefits to cover the cost of cooperation in the river basin plus administrative costs ($(ENB_j - (FNB_j + b_j^{ECO}))/ENB_j$). This new rule is described below.

$$FNB_j + b_j^{ECO} = (1-\gamma)ENB_j \tag{9}$$

where the left hand side of the equation is the final benefits after compensation and the right hand side is a percentage of the ENB. γ is chosen such that :

$$\sum_{j=1}^{J} b_j^{ECO} \leq E \tag{10}$$

and:

$$b_j^{ECO} \geq 0 \tag{11}$$

$$b_j^{ECO} \leq C_j \tag{12}$$

Equation 9 defines the benefit for each agent (b_j^{ECO}) as the difference between an agent's expected net benefits (ENB_j) and its final net benefits (FNB_j) plus a certain proportion of the expected net benefits. This proportion is defined as:

$$\gamma = (ENB_j - (FNB_j + b_j^{ECO}))/ENB_j \tag{13}$$

γ is the same for all agents. This ensures that each agent pays the same proportion of its ENB to cover the cost of cooperation over the basin.

Equation 10 defines the upper limit of the total benefits allocated to the agents and equations 11 and 12 define the lower and upper limits for the benefits allocated to each water user.

3 Results and Discussion

Figure 3 shows a schematic of the position of the agents in the Eastern Nile River basin, as modelled in the study by Arjoon et. al. (2016). The Grand Ethiopian Renaissance Dam (located at H8 in Figure 3) is online and there is increased irrigation in the upstream countries (Ethiopia and Sudan), representing a possible long term future scenario in the basin. This figure also highlights the three upstream irrigation agents that are rationed as a result of the economically efficient water allocation (I1, I4, I14). Other studies on optimizing water allocation in the Eastern Nile River basin have also concluded that irrigation should take place downstream in the basin and hydropower should dominate the upstream reaches (Arjoon et al, 2014; Whittington et al, 2005).

The results of applying three common bankruptcy based sharing rules (PRO, CEA, CEL), each having a different definition of equity, are compared to the results obtained in the application of the ECO sharing rule on the basis of the proportion of the expected net benefits (ENB) that water users pay toward the cost of cooperation. This basis of comparison was chosen because the goal of the new ECO sharing rule is to allocate the total benefit to the agents to ensure ”solidarity” in the basin, defined as the cost of cooperation being equally borne by all agents.

Results for the application of the CEA rule are shown in Figures 5 and 6 for hydropower water users and irrigators, respectively. These figures show the cost of cooperation paid by each water use agent, as a percentage of their ENB. Large filled squares are the mean cost and the small unfilled squares show the costs for each of 30 hydrological sequences that were analyzed. A high cost value means that the agent is paying a greater percentage of its ENB as cost of cooperation. The CEA rule favours the agents with the lowest claims (Figure 13). All agents are compensated for 100% of their claims with the exception of agents H8 and I22 who have the highest claim amounts. As a result, these two agents bear the burden of paying for the cost of cooperation between the two of them. Agent H8 is shown to have a wider variability in cost over the 30 hydrological scenarios, compared to agent I22. By definition of the rule, the cost is dependent only on the claim of the agent. In the case of I22, the claim depends on the marginal value of water at the site, since the agent receives 100% of their water demand in all scenarios. The claim for H8, on the other hand, depends not only on the marginal water value at this node, but on the value at the downstream node, both of which vary depending on the scenario. As well, the water allocation to the hydropower nodes also varies from one scenario to another.

Results for the application of the CEL rule are shown in Figure 7 for hydropower agents and Figure 8 for irrigation agents. The CEL rule favours the agents with the highest claims. The agents with the lowest claims do not necessarily have the highest initial ratios, which is a measure of the percentage of the expected benefits that are fulfilled through the use of water allocated to the agent ($\text{FNB}_j/\text{ENB}_j$). This can be

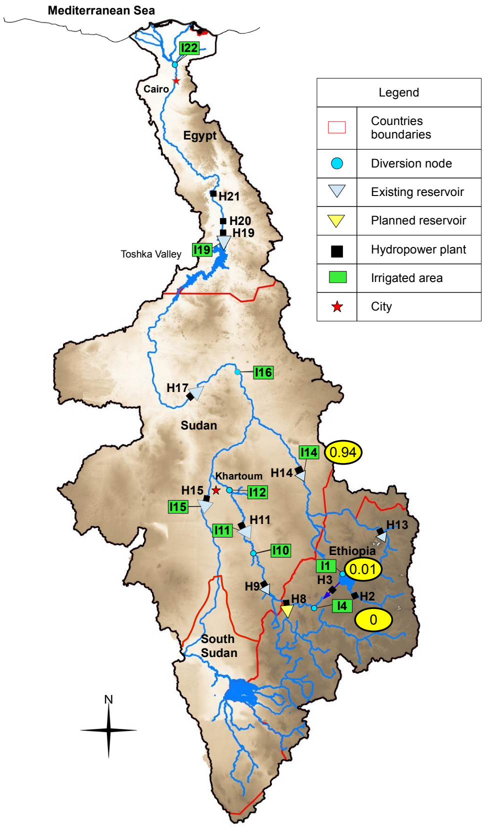

Fig. 3 Average proportion of water allocation to water demand for all agents. Only the values for those agents in which the proportion is less than 1 are shown (from Arjoon et al (2016)).

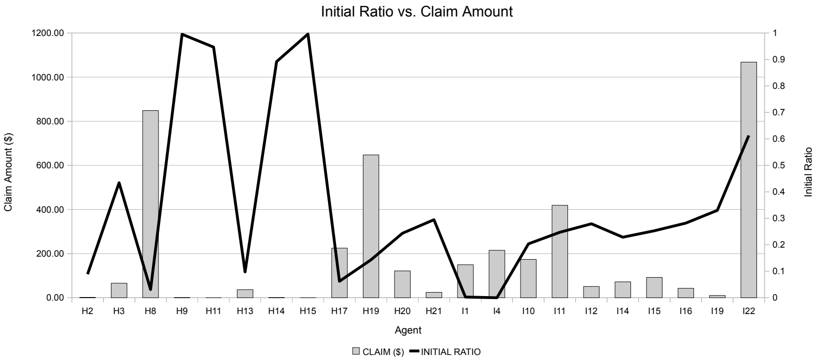

Fig. 4 Initial Ratio vs. Claim Amount ($)

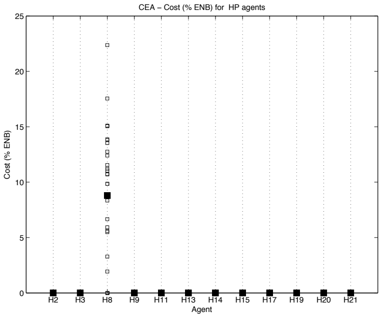

Fig. 5 % of ENB paid as cost of cooperation by HP users as determined by the CEA sharing rule.

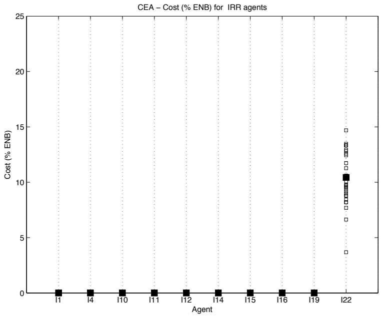

Fig. 6 % of ENB paid as cost of cooperation by IRR users as determined by the CEA sharing rule.

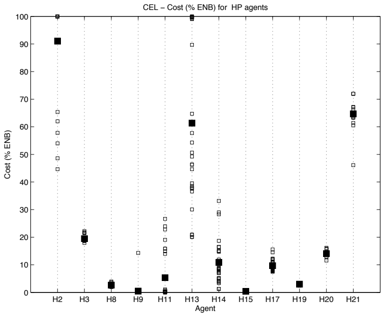

Fig. 7 % of ENB paid as cost of cooperation by HP users as determined by the CEL sharing rule.

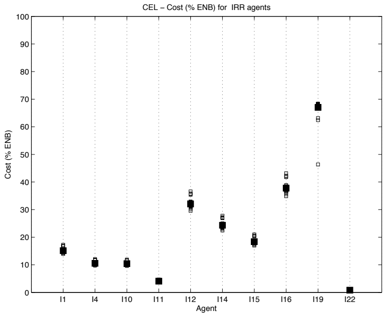

Fig. 8 % of ENB paid as cost of cooperation by IRR users as determined by the CEL sharing rule.

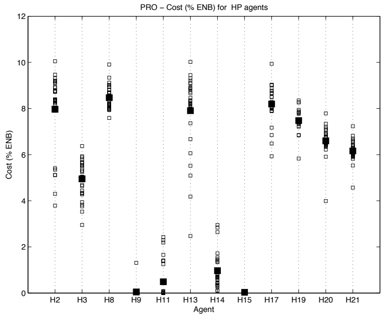

Fig. 9 % of ENB paid as cost of cooperation by HP users as determined by the PRO sharing rule.

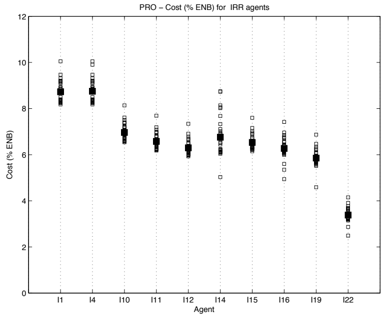

Fig. 10 % of ENB paid as cost of cooperation by IRR users as determined by the PRO sharing rule.

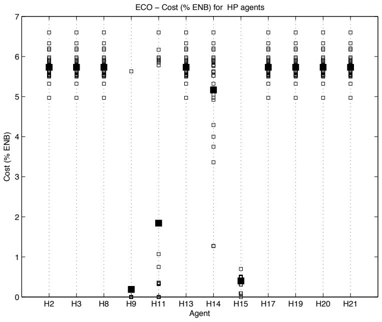

Fig. 11 % of ENB paid as cost of cooperation by HP users as determined by the ECO sharing rule.

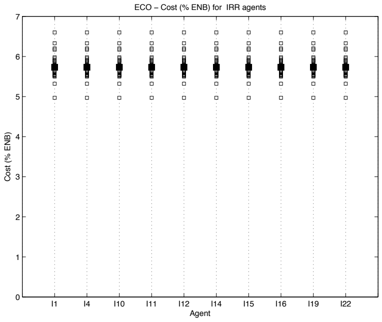

Fig. 12 % of ENB paid as cost of cooperation by IRR users as determined by the ECO sharing rule.

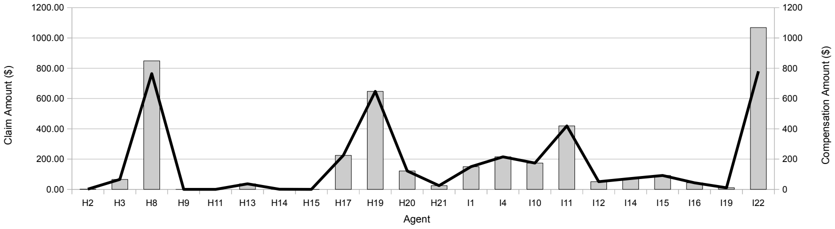

Fig. 13 Claim Amount ($) vs. Compensation Amount ($) for CEA sharing rule

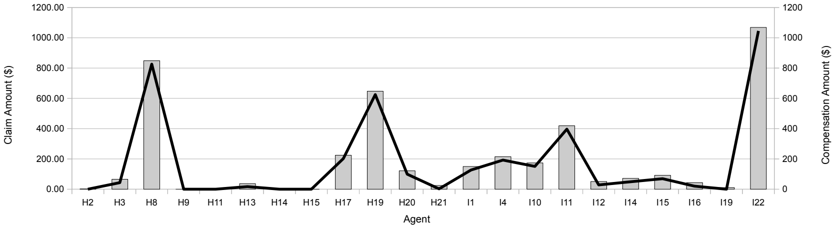

Fig. 14 Claim Amount ($) vs. Compensation Amount ($) for CEL sharing rule

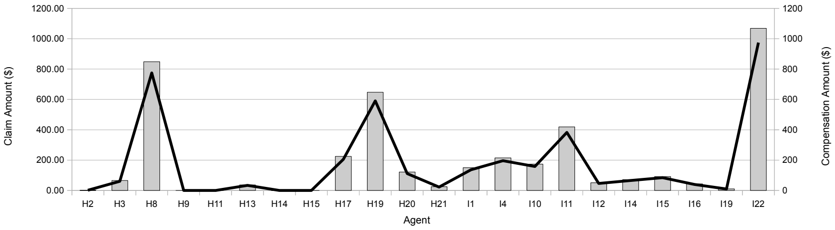

Fig. 15 Claim Amount ($) vs. Compensation Amount ($) for PRO sharing rule

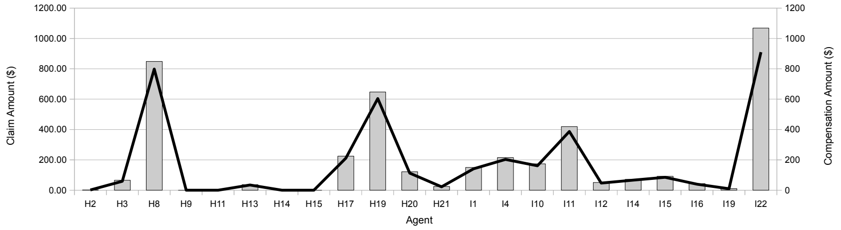

Fig. 16 Claim Amount ($) vs. Compensation Amount ($) for ECO sharing rule

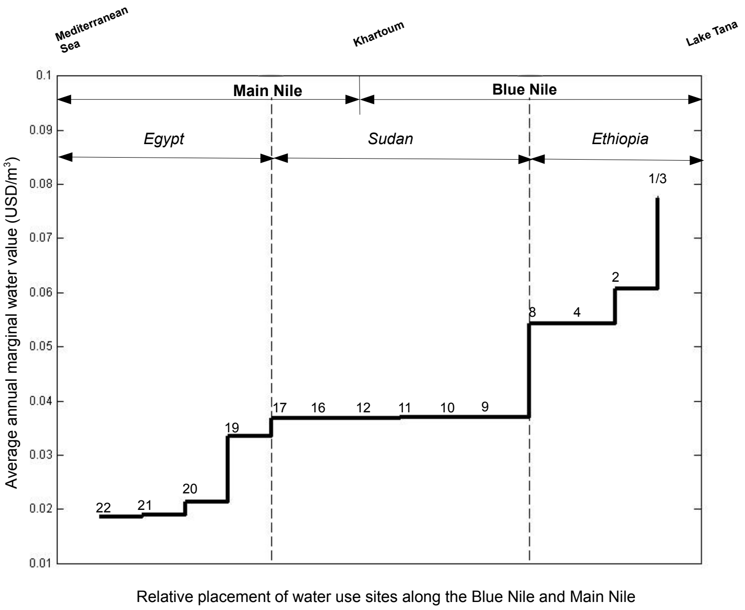

Fig. 17 Marginal value of water along the Blue and Main Nile Rivers (from Arjoon et al (2016)).

observed in Figure 4. Using the CEL sharing rule, these agents pay a higher cost of cooperation. For example, H2 pays the highest percentage of costs, on average. This agent has a low claim amount and receives no compensation using the CEL rule, but only gets 8.9% of its benefits from water use, as shown in Figures 4 and 14. This is compared to agent H9 who also has a low claim amount and no compensation but gets almost 100% of its benefits from water use and pays very little in cooperation costs. This difference results from the cost that each agent must pay for water. As seen in Figure 17, agent H2 pays the difference between the marginal value of water at site 2 and site 8. Agent H9, on the other hand, pays the difference in marginal value of water between site 9 and site 10. The cost of water for H2, then, is much greater than that for H9. The marginal value of water at a particular site is the sum of the values of all non-consumptive uses downstream, because each cubic meter of water used for a non-consumptive purpose (such as hydropower), at a particular site, is available for use downstream. Due to this cumulative effect of downstream productivities for non-consumptive uses, the marginal value of water at a particular site is generally greater than that at a downstream site (depending on the configuration of infrastructure in the river basin). As a result, agent H9 pays very little in costs and receives almost 100% of the benefits from water use while agent H2 pays a larger percentage of its benefits from water use as water costs. The agents favoured with this sharing rule are H8, H9, I11 and I22, who are always fully compensated, regardless of the hydrological scenario, because they always have the highest claims. Figures 7 and 8 show that all of the other agents have different degrees of variability in cost allocation over the 30 scenarios. Again, the hydropower users show more variability for the reasons explained above for the CEA rule.

Although all agents receive the same proportion of their claims using the PRO sharing method (Figure 15), this rule favours those agents who have a large initial ratio to begin with. For example, I1, I4 and H8 have the lowest initial ratios (Figure 4) but pay the highest percentage of benefits as costs. The costs, using this sharing rule, are also variable for all agents over the 30 hydrological scenarios, because the compensation is proportional to the claims and the the claims vary according to hydrological conditions (hydrological scenarios) (Figures 9 and 10). Because, once again, this rule is based on the claims of the agent only, the hydropower agents experience a greater spread of cost over the hydrological scenarios. On average, however, the variability is relatively low with the difference between the low cost scenario and high costs scenario measuring about 3% of the ENB.

Using the newly developed sharing rule (ECO), agents receive varying proportions of their claims to ensure that they all finally pay the same costs of cooperation, as a proportion of their ENB. As seen in Figure 11, agents H9, H11, H14 and H15 actually have lower cooperation costs, on average. This results from the property that no agent gets a negative amount of compensation. These agents have initial ratios higher than the final ratio ($(\mathrm{FNB}_j + \mathrm{b}_j)/\mathrm{ENB}_j$) obtained for all agents after the estate is shared. As a result, although they do not get any compensation, their final costs are lower than those of the other agents. Again, these are the agents that pay the least for water because the marginal water values at the site of water abstraction and downstream are similar (Figure 17). The variability of costs over the 30 hydrological sequences is similar for all agents, regardless of the sector to which they belong. Because the calculations are based on the initial and final ratios, and not the actual claim amount, this nullifies the effect of the variability in the difference between water allocation and water demand. In actuality, the range of variability is low (around 2% of the ENB depending on the hydrologic scenario). Only H14 has high variability because this agent receives very little in compensation.

CEA and CEL are egalitarian sharing rules. The equity consideration of these rules is that all agents should have equal rights to the estate (either as benefits or losses). For the PRO sharing rule, there is inequality in the amounts received by each agent, however, priority of one agent over another is ruled out because they all receive the same percentage of their claim. As well, proportional rules, in general, spread the shortages over all agents. In all of these sharing rules, the property of ”equal treatment of equals” applies, meaning that agents with equal claims will receive the same amounts of benefits, regardless of the benefits received from water use.

In comparison to the common bankruptcy rules, the proposed ECO rule distributes the estate by taking into account the benefits already received through water allocation, measured as the initial ratio of an agent. Based on this approach, agents with smaller initial ratios are entitled to a higher percentage of compensation based on their claim. Note that the property of ”equal treatment for equals” does not apply in this sharing rule.

4 Conclusions

The sharing of economic benefits in transboundary river basins poses numerous challenges for water managers and policy makers. One of these is in addressing the issue of equitability, which is often difficult to define and to operationalize. In a recent paper, the authors present an institutional arrangement in which water is efficiently allocated across a transboundary river basin and the benefits of the resulting water use are equitably shared. The methodology is made up of 4 steps: 1) water users bid for an amount of water, or they supply data so that their demand curve can be derived; 2) a hydro-economic model is used to determine the efficient water allocation over the basin, and the corresponding marginal value of water at each user site; 3) water users are charged for the water allocated to them; 4) the total payment for water use, over the basin, is redistributed back to the water users in an equitable manner using a sharing rule developed specifically for the basin, based on a stakeholder definition of equity. The authors developed a sharing rule (ECO), based on bankruptcy methods, to allocate the cost of cooperation in the Eastern Nile River basin case study. The cost of cooperation is defined as the monetary value of benefits lost to a user due to the application of basin-wide efficient allocation policies. The rule ensures that this cost is equally covered by all water users. The main feature of the ECO rule is that it shares the costs while taking into account the total benefits that water users receive from two sources: 1) benefits from the use of water directly allocated to them and 2) monetary transfer payments.

In this paper, we compare the ECO rule to three common bankruptcy rules (PRO, CEA, CEL) and discuss how the use of the ECO rule may be more acceptable to the parties concerned. The results show that the ECO rule allocates transfer payments in such a way as to equalize the proportion of cost to expected net benefits that the agents pay.

It should be stressed that this proposed rule is based on certain properties that may define equity in the sharing of benefits in a river basin, mainly that cooperation costs should be shared in equal proportion over the water users in the basin. As discussed in Arjoon et al (2016), equity considerations may be different for each river basin. The definition of equity must be defined with respect to social, political, cultural, economic, and ecological features of the specific transboundary basin. In acknowledging the differences in the notion of equity in different basins, there is a need to define sharing rules that apply the properties specific to each basin. Analytical methods, and specifically bankruptcy methods, with their relative simplicity and flexibility, show promise as useful tools to solve these types of problems.

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Appendix B

Supplementary papers

I

Economic Value of Storage in Multireservoir Systems

Amaury Tilmant, Diane Arjoon,
and Guilherme Fernandes Marques

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2012

Après trois décennies d'investissement anémiques dans les barrages, de nombreuses régions à travers le monde cherchent à développer de nouvelles capacités de stockage à la fois pour répondre à la demande croissante pour l'eau et se prémunir contre le risque posé par le changement climatique. La capacité de stockage est souvent perçue comme un élément clé des stratégies d'adaptation au changement climatique parce qu'elle contribue au développement socio-économique grâce à l'irrigation, la production d'énergie, la pêche, et l'approvisionnement en eau pour l'industrie et les municipalités. Les bénéfices retirés des barrages doivent compenser les coûts environnementaux occasionnées par la dégradation des écosystèmes et les coûts sociaux résultant du déplacement des personnes affectées par la montée des eaux. Les avantages du stockage proviennent essentiellement de la capacité de déplacer l'eau pendant la saison sèche alors que l'eau devient si précieuse. Compte tenu que les bassins fluviaux sont de plus en plus exploités pour la construction de nouveaux barrages, il pourrait être important aux fins de planification et d'exploitation d'évaluer la contribution de chaque réservoir au bénéfice du stockage. Cet article présente une méthode permettant de déterminer la valeur économique du stockage dans des bassins comportant plusieurs réservoirs, sur la base du bénéfice net marginal de stockage et sur la modélisation hydro-économique. Une série de réservoirs dans le bassin du fleuve Euphrate est utilisé pour illustrer la méthodologie.

Economic Value of Storage in Multireservoir Systems

Amaury Tilmant[1]; Diane Arjoon[2]; and Guilherme Fernandes Marques[3]

Abstract: Following three decades of rather low investment in dams, many regions throughout the world are now seeking to further develop new storage capacity to meet exploding demands for water and to hedge against the risk posed by climate change. Storage capacity is often perceived as a key element of climate change adaptation strategies, while at the same time contributing to socioeconomic development through irrigation, energy generation, fish production, and municipal and industrial water supply. The benefits provided by dams must be balanced with the associated environmental and social costs, which can take various forms, such as the degradation of ecosystems because of altered flow regimes and the relocation of people from the impoundment area. The benefits of storage essentially come from the ability to move water in time, making it available during the low-flow season when it becomes more valuable. As river basins develop and new dams are constructed, it may be important for planning and operational purposes to assess the individual contribution of each reservoir to the benefits of storage. This paper presents a methodology to determine the economic value of storage in multireservoir systems based on the marginal net benefit functions of storage and on hydroeconomic modeling. A cascade of reservoirs in the Euphrates river basin is used to illustrate the methodology. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000335.

Author keywords: Storage; Hydropower; Reservoir operation; Hydro-economic modelling.

Introduction

One of the difficulties in managing water resources comes from the fact that water supply and demand often do not coincide, either in space or time. To deal with the timing issue, one can resort to storage, which can be classified into four categories: (1) large reservoirs, (2) small reservoirs, (3) underground aquifers, and (4) the vadoze zone (Keller et al. 2000). The distinction between small and large reservoirs is based on the standard height criterion suggested by the International Commission on Large Dams (a structure less than 15-m high is considered to be a small dam). Small dams are primarily used to meet punctual demands, whereas large dams are better suited to deal with larger spatial and temporal imbalances between supply and demand (typically multiseason to multiyear at a regional scale). Regardless of the category, the basic principle remains the same: to store water when supply exceeds demand (when the marginal water value is low) to make it available when demand is greater than supply. The ability to move water in time is the essential service offered by storage and, as such, this service can generate substantial benefits in terms of energy generation, food production, flood control, and municipal and industrial water supply.

For the dam industry, the 20th century was marked by two periods. The pre-1980 period saw the construction of numerous dams all over the world, especially in industrialized countries. By the late 1970s, most of the European and North American countries had achieved such a level of development that the remaining projects left on the drawing boards were essentially neither economically viable nor socially acceptable. At that time, while the focus was shifting to developing countries, dam builders were facing growing opposition led by environmentalists, mostly from developed countries (Biswas and Tortajada 2001). The bone of contention was related to the social and environmental costs of dams, which had not been properly considered during the planning phase of most projects. The debate led to the establishment of the World Commission on Dams (WCD), which was initiated by International Union for Conservation of Nature (IUCN) and the World Bank. The report, released in 2000 (WCD 2000), made several recommendations to improve the economic, social, and environmental performances of large-scale hydraulic infrastructure. The dam industry, donors, and governments were forced to adopt precautionary principles, which slowed the development of new water resource structures. More than 20 years later, as a result of this policy, countries in Africa can store only about 4% of annual renewable flows, compared with 70%–90% in many developed countries (UNESCO 2009). Expressed in terms of per capita storage, the difference between western countries and Africa is just as staggering: 3,500 m^3 compared with 50 m^3.

This underinvestment in hydraulic infrastructure in Africa means that the agricultural sector, which still plays an important role in terms of food and employment, is vulnerable to erratic climatic conditions. More generally, recent ex ante studies have shown a positive relationship between gross domestic product (GDP) and investments in large-scale water resource projects such as irrigation schemes, hydropower stations, water supply, and sanitation (Bathia et al. 2009; Shah and Kumar 2008; Strzepek et al. 2008). This issue is now tackled by African leaders through the New Partnership for Africa's Development (NEPAD), which is an attempt to attract investments in various sectors, including water. However, the global financial crisis that began in 2007 in the United States and Europe is a new source of uncertainty as traditional western bilateral and multilateral donors may be tempted to reduce their budgets. But China has now become a major alternative

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lender, providing competitive financial packages often linked to infrastructure projects like dams (Naidu and Mbazima 2008).

For water resources planners, this renewed impetus for large storage projects is an opportunity to learn lessons from the past and to internalize the externalities inherent to such projects, especially the social and environmental costs. These costs must be balanced with the benefits associated with a greater and more reliable yield that comes with a large storage capacity. Assessing the benefits of storage when a new project is added to a system with multiple reservoirs is not straightforward as it will depend on various factors, including the configuration of the system (where the new project is located in ralation to other dams), its relative storage capacity, its operational objectives, whether it will be managed individually or in conjunction with other reservoirs, etc.

Several studies have attempted to assess the economic value of storage. For example, Goor et al. (2010) showed that the storage capacity of the planned four megadams in the Blue Nile in Ethiopia would correspond to 14% of the short-run annual benefits for the Eastern Nile River basin, which already includes six reservoirs in Sudan and Egypt. A similar study (Tilmant et al. 2012) found that the economic value associated with the three largest existing reservoirs in the Zambezi River basin in Africa corresponds to 443 million US$/year, i.e., 17% of the basin-wide benefits. These two studies rely on hydroeconomic modeling and scenario analysis to derive the value of storage; the economic performances of the systems are compared with and without the reservoirs. The main limitation of the with-without analysis approach is that it does not directly provide the individual contribution of each reservoir to the economic performance of the entire system, which might be relevant when the reservoirs belong to different owners (e.g., power companies, countries) and/or when their individual performance is expected to be influenced by new storage infrastructure. The knowledge of the value of storage can also be relevant when designing a benefit-sharing mechanism whereby downstream users would, for example, compensate the owner of the reservoir for the storage services (Braden and Johnston 2004). Another example where the value of storage in individual reservoirs is meaningful is the debate surrounding the implementation of environmental flows and the reoperation of a system of reservoirs for ecological purposes (Suen and Eheart 2006). As well, it would be important to assess the value of storage of potential reservoirs, prior to construction, to demonstrate that the new infrastructure would bring value to the river basin system. One of the key recommendations of the World Commission on Dams is that "A dam should not be constructed in a shared river if other riparian States raise an objection ... " (WCD 2000). Knowing the value of a proposed reservoir could be important in ensuring the cooperation of riparian states.

This study addresses the limitations of the with-without analysis and the need to know the individual contribution of reservoirs to basin-wide benefits by considering reservoirs as economic agents characterized by their marginal net benefit function. In economics, the marginal net benefit function for water represents the user's willingness to pay for various quantities of water, i.e., the demand for water. This study will concentrate on the marginal net benefit for storing raw water in a particular reservoir for later use by different users/sectors. Based on this function, one can determine the economic value associated with changes in storage from the reservoir operating policies and the marginal value of water stored in those reservoirs. This information can nowadays be obtained from large-scale multireservoir optimization models. This paper is organized as follows: the methodology, the multireservoir optimization model and the case study are described, followed by a presentation and discussion of the simulation results and, finally, conclusions.

Materials and Methods

Value of Storage Services

As previously mentioned, the proposed approach to assessing the economic value of storage considers that reservoirs are economic agents offering the basic service of transfering water in time. This is illustrated by a simple example described in Pereira (1998) with a run-of-river power plant and an upstream reservoir (Fig. 1). This system is shared by two parties: the owner of the reservoir and the owner of the power plant. Let t be the index of time period, $q_t(j)$ be the natural inflows at site j during period t, $s_t(j)$ be the volume in storage at the beginning of period t at site j, and $r_t(j)$ be the release during period t at site j. Ignoring evaporation and spillage losses for notational simplicity, the water balance constraints for this simple hydro system are

$$r_t(1) = s_t(1) - s_{t+1}(1) + q_t(1) \tag{1}$$

$$r_t(2) = q_t(2) + r_t(1) \tag{2}$$

Substituting Eq. (1) in Eq. (2) gives

$$\begin{aligned} r_t(2) - q_t(1) &= q_t(2) + s_t(1) - s_{t+1}(1) \\ r_t(2) &= q_t(2) + q_t(1) + \Delta s_t(1) \end{aligned} \tag{3}$$

Denoting c as the production coefficient of the hydropower plant ($\mathrm{MW \cdot h/m^3}$) and π as the energy price ($\mathrm{US\$/MW \cdot h}$), the revenues of the hydropower plant can be obtained after multiplying both sides of Eq. (3) by πc

$$\pi c r_t(2) = \pi c[q_t(2) + q_t(1)] + \pi c \Delta s_t(1) \tag{4}$$

From Eq. (4), can be seen that the revenues of the hydropower plant can be subdivided into two components: a natural one and a regulated one. The natural component is the portion of revenue originating from natural inflows to the system, i.e., $q_t(2) + q_t(1)$, whereas the second component comes from the upstream reservoir and its ability to transfer water in time $\Delta s_t(1)$. This second component corresponds to the economic value of storage.

This concept can be generalized and applied to any system with J multipurpose reservoirs operated over several within-the-year time periods ($t = 1, 2, \ldots, nt$). To achieve this, for each reservoir, the marginal net benefit function indicating the relationship between the marginal value of water stored in the reservoir and the storage volume is needed. At any given site in the system, the marginal value of water λ gives the net benefits associated with an extra unit of water available at that site. When dealing with water

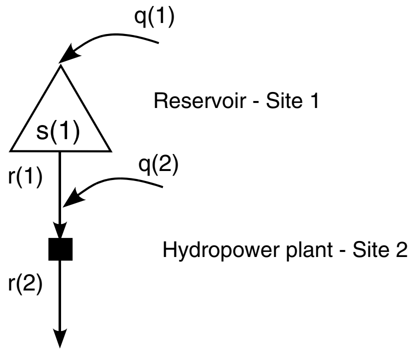

Fig. 1. Example with one hydropower plant and one upstream reservoir

allocation problems across different users/sectors, one must use the so-called at-source water value, which is the value of the last unit available in the river/reservoir system before it is diverted to the users (Young 2005). Because the change in water availability in any reservoir can come not only from changes in allocation decisions related to the specific schemes supplied by the reservoir (e.g., irrigation cities, power companies) but also from allocation decisions taken upstream (i.e., change in upstream reservoirs releases), the value of storage in any particular reservoir will reflect basin-wide (im)balances between supply and demand. For the jth reservoir, the marginal net benefit function at time t is denoted by $M_t[s_t(j)]$, and the area beneath the curve indicates the benefits associated with a change in storage during that period. For example, imagine that the storage at the beginning of time period t is A, then the benefits of moving from $s_t(j) = A$ to $s_{t+1}(j) = B$ corresponds to

$$V_t(j) = \int_A^B M_t[s_t(j)]ds_t(j) \tag{5}$$

which is the shaded area under the marginal net benefit function M_t (Fig. 2). For short time periods, Eq. (5) can be approximated by $\lambda_t(j)|\Delta s_t(j)|$ given that both the change in storage and marginal water value will be relatively small. The annual value of storage V_y of a system with multiple reservoirs is the summation over the nt periods constituting a year and over the J reservoirs

$$V_y \approx \sum_{t=1}^{nt}\sum_{j=1}^{J} \lambda_t(j)|\Delta s_t(j)| \tag{6}$$

In the remainder of this paper, because there is not an analytical expression for the J marginal net benefit functions for storage M_t, the economic value of storage will be calculated with Eq. (6), which only requires changes in storage and the marginal water values in each reservoir. This information can, for instance, be obtained from hydroeconomic optimization models that integrate spatially distributed water resources, economic values, infrastructure, and management policies (Harou et al. 2009; Heinz et al. 2007). Economic water demands, which are value (scarcity) sensitive, are integrated into a network built around arcs and nodes: the former usually represent natural inflows to the system, canals, and the river network, whereas the nodes represent confluences, reservoirs, abstraction points, and demand sites. At the optimal solution, the optimization model provides the allocation policies and the shadow prices associated with the constraints. When the constraint is a water balance equation, like the mass balance in a reservoir, the shadow price corresponds to the marginal value of water in that reservoir. Examples of hydroeconomic optimization models can be found in Rosegrant et al. (2000), Cai et al. (2003), Ward et al. (2006), and Fisher et al. (2005). Here, the multipurpose multireservoir operation problem is solved using stochastic dual dynamic programming (SDDP). The next section briefly describes the SDDP algorithm.

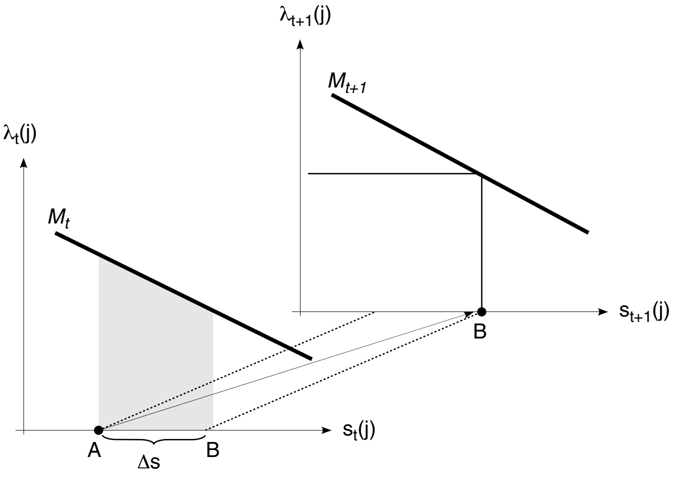

Fig. 2. Marginal net benefit function and the value of change in storage

Multireservoir Optimization Model SDDP

The multireservoir operation problem can be mathematically represented as a multistage, stochastic, nonlinear optimization problem. Denote t as the index of time (stage), T as the end of the planning period, b_t as the one-stage benefit function at stage t, $\mathbf{u}_t$ as the vector of allocation (decision) variables, $\mathbf{s}_t$ as the vector of storage at the beginning of t, $\mathbf{q}_t$ as the vector of stochastic inflows, $\mathbf{e}_t$ as the vector of evaporation losses, α as the discount factor, v as a terminal value function, and $\mathbb{E}$ as the expectation operator. The expected benefits Z to be maximized from the operation of the system from period 1 until period T can be written as

$$Z = \mathop{\mathbb{E}}_{\mathbf{q}_t}\left[\sum_{t=1}^{T} \alpha_t b_t(\mathbf{s}_t, \mathbf{u}_t, \mathbf{q}_t) + \alpha_{T+1} v(\mathbf{s}_{T+1}, \mathbf{q}_T,)\right] \tag{7}$$

subject to the following constraints

$$\underline{\mathbf{u}}_{t+1} \leq \mathbf{u}_{t+1} \leq \bar{\mathbf{u}}_{t+1} \tag{8}$$

$$\underline{\mathbf{s}}_{t+1} \leq \mathbf{s}_{t+1} \leq \bar{\mathbf{s}}_{t+1} \tag{9}$$

$$\mathbf{s}_{t+1} = \mathbf{s}_t - \mathbf{C}\mathbf{u}_t + \mathbf{q}_t - \mathbf{e}_t \tag{10}$$

where $\mathbf{C}$ = connectivity matrix linking the different reservoirs. The vector of shadow prices associated with constraint (10) is λ_t.

Stochastic dynamic programming (SDP) can be used to recursively solve the optimization problem of Eqs. (7)–(10)

$$F_t(\mathbf{s}_t, \mathbf{q}_{t-1}) = \max_{\mathbf{u}_t}\{\mathop{\mathbb{E}}_{\mathbf{q}_t|\mathbf{q}_{t-1}}[b_t(\mathbf{s}_t, \mathbf{u}_t, \mathbf{q}_t) + \alpha_{t+1} F_{t+1}(\mathbf{s}_{t+1}, \mathbf{q}_t)]\} \tag{11}$$

where F_{t+1} = benefit-to-go function. At the optimal solution, both SDP-derived release policy tables $r_t^*(s_t, q_{t-1})$ and the shadow prices associated with Eqs. (8)–(10) are available and can be used to calculate V_y.

The solution to Eq. (11) requires the discretization of the state space, which leads to an exponential growth of the number of combinations of discrete states that quickly become overwhelming even for modern computers (this is the so-called curse of dimensionality). To deal with the dimensionality issue, the reservoir operation problem is solved with SDDP, an extension of SDP that can handle a much larger state-space. The remainder of this section presents an overview of SDDP. The reader should refer to Tilmant et al. (2008) for a comprehensive description of the algorithm.

In SDDP, the benefit-to-go function F_{t+1} is approximated by a series of hyperplanes that provide an upper bound to F_{t+1}. The one-stage SDDP optimization problem becomes

$$F_t(\mathbf{s}_t, \mathbf{q}_{t-1}) = \max_{\mathbf{u}_t}[b_t(\mathbf{s}_t, \mathbf{u}_t, \mathbf{q}_t) + \alpha_{t+1} F_{t+1}] \tag{12}$$

subject to Eqs. (8)–(10) as well as the following restrictions on F_{t+1}

$$\begin{cases} F_{t+1} - \boldsymbol{k}_{t+1}^{1}\mathbf{u}_{t+1} \leq \boldsymbol{\gamma}_{t+1}^{1}\mathbf{q}_{t} + \boldsymbol{\beta}_{t+1}^{1} \\ \vdots \\ F_{t+1} - \boldsymbol{k}_{t+1}^{L}\mathbf{u}_{t+1} \leq \boldsymbol{\gamma}_{t+1}^{L}\mathbf{q}_{t} + \boldsymbol{\beta}_{t+1}^{L} \end{cases} \tag{13}$$

where L = number of hyperplanes; and $\boldsymbol{k}_{t+1}^{l}$, $\boldsymbol{\gamma}_{t+1}^{l}$ and $\boldsymbol{\beta}_{t+1}^{l}$ = parameters of the lth expected hyperplane calculated from the primal and dual information available at stage $t+1$.

The solution to the SDDP algorithm is an iterative procedure. It starts with a forward pass in which the parameters of the hyperplanes are set to zero (the model seeks to maximize immediate benefits, therefore choosing "myopic" decisions). The forward pass corresponds to a Monte Carlo simulation phase in which the system is simulated many times with different hydrologic sequences. At the end of the first forward phase, the model is ready to reverse direction and move backward using the trajectory $\{\mathbf{s}_1^1, \mathbf{s}_2^1, \ldots, \mathbf{s}_T^1\}$ previously identified. At stage T, the initial storage is $\mathbf{s}_T^1$ and the one-stage optimization problem is solved for each sampled value of $\mathbf{q}_T$. The corresponding primal and dual information is then used to determine the parameters of the expected hyperplane, which is then passed to previous time period $T-1$ where it provides an upper bound to F_T. This backward optimization procedure continues until it reaches the first stage $t=1$. Hence, when the algorithm moves backward, problems are solved using the trajectories identified during the forward iteration phases, but there are now additional constraints in the form of hyperplanes for the problem to use. Each time the algorithm makes an iteration, a new trajectory is made available for the forward phase and more hyperplanes are added, therefore refining the approximation of F_{t+1}, as illustrated in Fig. 3. This process continues until the model converges to a solution (Philpott and Guan 2008).

The SDDP algorithm also relies on an analytical representation of the hydrologic uncertainty, which limits the computational effort required to solve the optimization problem by preventing the discretization of the hydrologic state variable (as in SDP). In the forward pass, the hydrologic model also generates synthetic flow sequences that are used to simulate the system and check the accuracy of the approximation of the piecewise linear benefit-to-go functions. Another advantage of using synthetic flow series in the forward pass is that one can increase the number of simulations to get smoother empirical statistical distributions. The disadvantages are mainly related to the structure of the hydrologic model, a periodic autoregressive model with cross-correlated

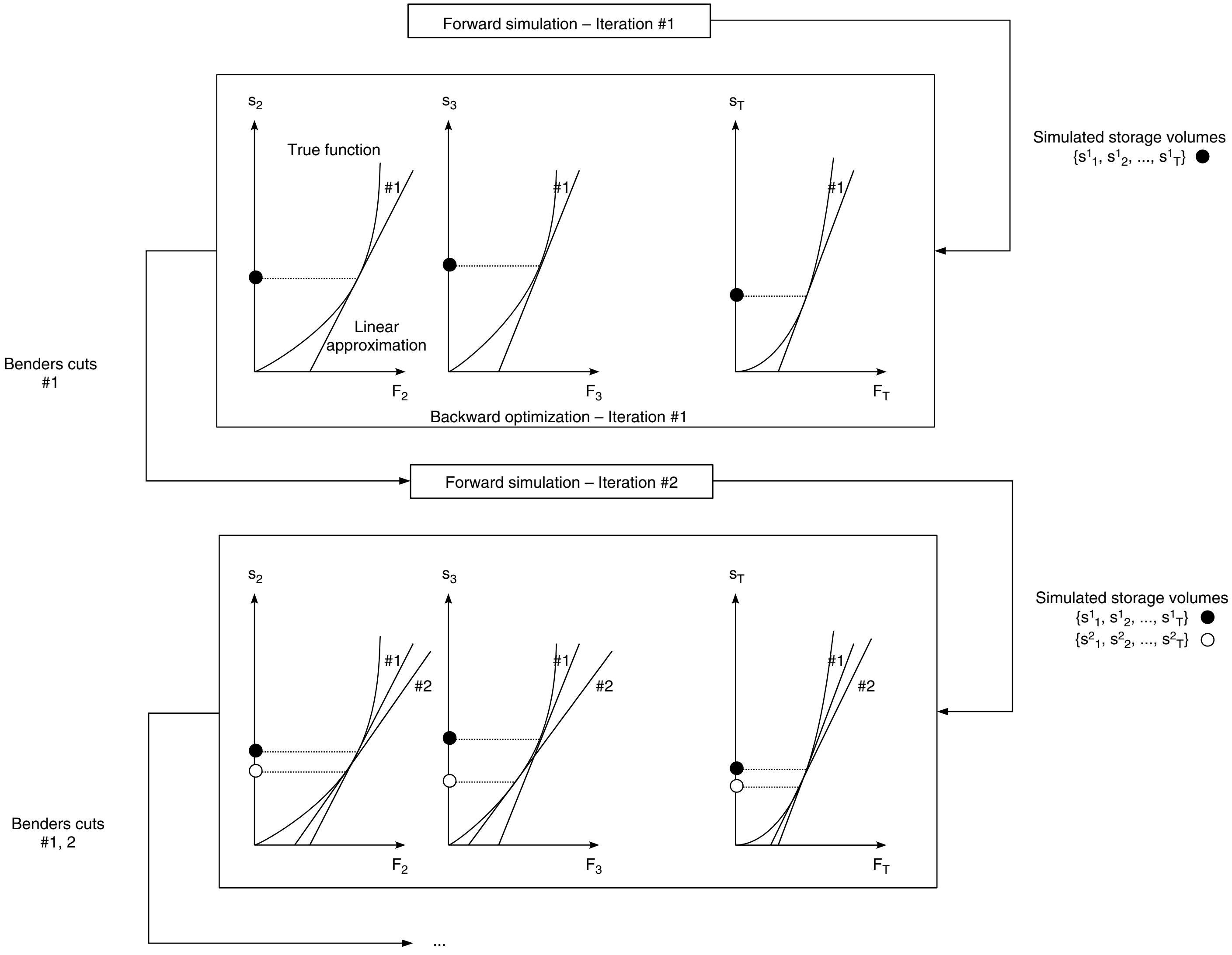

Fig. 3. Iteration between the forward and backward phases

residuals, which does not necessarily preserve the long-term memory of the hydrologic processes.

Once the optimization problem is solved (the SDDP model has converged), the results of the last forward simulation phase can be used to analyze the performance of the system. In contrast to SDP, the SDDP model does not provide the traditional release policy tables $r_t^*(s_t, q_{t-1})$. The model, rather, provides a set of piecewise, linear benefit-to-go functions, which can further be used for the operational management of the water resources system. Other results of interest are the vectors of marginal values of water $\boldsymbol{\lambda}_t$ and the vectors of simulated storage volumes $\mathbf{s}_t$. Together, they will be used to determine the economic value of storage in the cascade of multipurpose reservoirs in the Euphrates River basin.

Euphrates River Basin in Turkey and Syria

The Euphrates River, one of the longest rivers in southwest Asia, flows from Turkey to Iraq where it merges with the Tigris River before discharging into the Persian Gulf (Fig. 4). Irrigated agriculture has always been an important activity in this region; some of the first hydraulic societies emerged in the fertile plains delineated by these two rivers. More recently, the headwaters have attracted the attention of water planners, and major irrigation and hydropower schemes have been developed over the last 30 years. In Turkey, the Great Anatolia Project (GAP) is a large-scale project that involves the construction of 22 reservoirs and 19 hydropower stations, and the irrigation of 1.7×10^6 ha in the Turkish part of the Euphrates-Tigris River basin (Kolars and Mitchell 1994). However, most of the attention is on the Euphrates River where the GAP is expected to reduce the flow by 30–50% (Beaumont 1998) and alter the natural flow regime as a result of the big reservoirs. In Syria, the Tabqa scheme diverts the Euphrates water to irrigate the left and right banks of the Euphrates while generating $2.3\ \text{TW} \cdot \text{h/year}$ of energy. Compared to consumptive uses from the agricultural sector (evapotranspiration) and from the hydropower sector (evaporation losses), domestic and industrial uses in the upper reaches of the Euphrates are negligible and are thus ignored in this analysis.

For water resources planners in both countries, the highly contrasted hydrologic regime of the Euphrates River could only be dealt with through storage. With 70% of the river discharge taking place during the spring, from April to June, the reservoirs are expected to refill quickly before being slowly drawn down until the next spring snowmelt. The flow regime is also characterized by a significant interannual variability; at the Syro-Turkish border, annual discharges range from 15,260 to 42,700 hm^3/year. Moreover, the fact that Turkey contributes to more than 90% of the annual discharge of the Euphrates has always been put forward by Turkish authorities to justify the GAP and the right to consume water on Turkish territory before it crosses the border.

The GAP and the Tabqa projects are good examples of water resources developments that have been carried out without much cooperation and coordination among riparian countries. This study considers that the irrigation schemes have indeed been developed unilaterally by each country, but it assumes that the reservoirs are

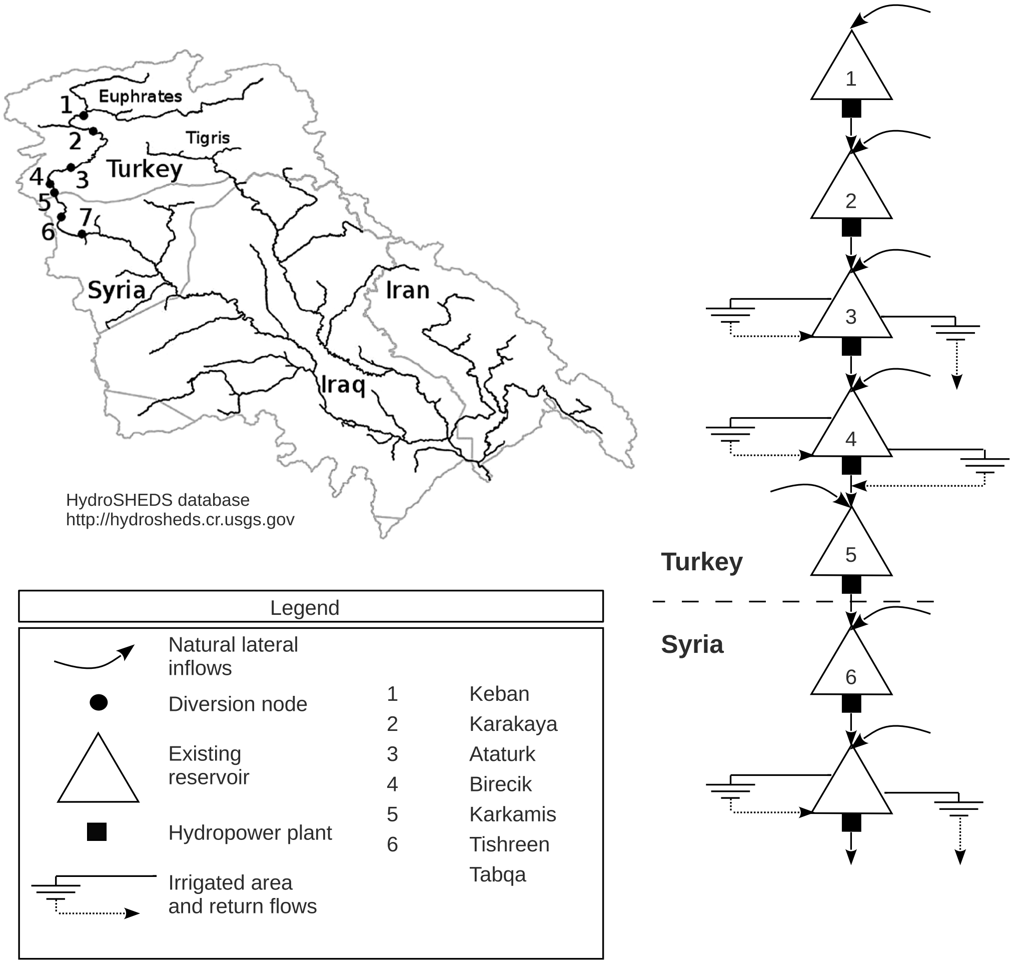

Fig. 4. Euphrates-Tigris River basin and the cascade of reservoirs in Turkey and Syria (map data from USGS HydroSHEDS, http://hydrosheds.cr.usgs.gov)

conjunctively managed for the production of hydroelectricity. Even though this assumption does not reflect the current situation, it is not expected to have a significant impact on the performance of the system because the installed capacity of the Tabqa power station is less than 10% of its Turkish counterparts. Moreover, in terms of storage capacity, Lake Assad represents less than 15% of the total storage in Turkey.

Stochastic Dual Dynamic Programming Model of the Euphrates River

The SDDP model of the Euphrates River in Turkey and Syria includes seven hydropower plants and six irrigation demand sites supplied by the Ataturk, Birecik, and Tabqa reservoirs. Fig. 4 shows a schematization of the system, and Table 1 lists the main characteristics of these infrastructures.

When dealing with hydroelectric reservoir operation problems, it is fairly common to adopt a time decomposition approach in which a sequence of models, with different time frames, are developed and implemented. This approach starts with long-term planning models (monthly time step and over-year planning horizon), which provide future marginal water values and storage levels. This information constitutes the boundary conditions for mid- and short-term optimization tools (from weekly to daily time horizon), which, in turn, feed real-time operation models focusing on load dispatching, unit commitment, and transmission constraints. The SDDP model used in this study clearly belongs to the first class (strategic planning) as it determines optimal allocation decisions (e.g., reservoirs releases and irrigation withdrawals) over a planning period of 5 years on a monthly time step. These results can then be refined using short-term optimization models, should the data be available. Because of data constraints, the proposed methodology to determine the economic value of storage will be illustrated using a strategic planning model only (but there is no conceptual difficulty in refining it using short-term management tools as long as they can provide the marginal water values and the changes in storage).

In the Euphrates, previous studies have shown that a 5-year planning period adequately dealt with the multiyear storage capacity of some of the reservoirs listed in Table 1 (Tilmant and Kelman 2007; Tilmant et al. 2008). However, simulation results are analyzed for year 3 only to avoid the initial hydrological and storage conditions and the end-effect distortion attributable to the reservoirs' depletion that happens as the end of the planning period approaches. The forward simulation phase of SDDP relies on 40 synthetic monthly inflow sequences that are assumed to be representative of the stochastic process governing the hydrology in the basin. This project deals with mid- to long-term reservoir operation planning problems where the availability of water must obviously be considered as stochastic.

To calculate the net benefits from the power sector, the value of electricity π_t is needed, which is the short-run marginal cost (SRMC) of the corresponding hydrothermal electrical system. In Turkey, gas-fired power plants are likely to become the marginal units (Tilmant and Kelman 2007). The SRMC is thus expected to correspond to the variable cost of such power plants, i.e., US\$40/MW · h. In Syria, the SRMC is higher because hydropower will displace more costly oil-fired power plants whose variable costs exceed US\$55/MW · h.

Table 1. Majors Dams Considered in the SDDP Model

Name	Rated capacity (MW)	Storage capacity (km^3)	Irrigation (ha)
Keban	1,240	31.0	—
Karakaya	1,800	9.58	—
Ataturk	2,400	48.7	476,000
Birecik	672	1.22	92,000
Karkamis	180	0.157	—
Tishreen	630	1.88	—
Tabqa	880	14.16	198,000

The parameters required to calculate the net short-run returns to irrigation water for the two main crops (wheat and cotton) are taken from Tilmant et al. (2008). These include net returns of US\$230/ha and US\$800/ha for wheat and cotton respectively, irrigation efficiency of 45% for both crops and return flows of 30% for both crops.

Analysis of Optimization Results

After convergence, the SDDP model provides a variety of results, including the optimal allocation decisions, i.e., turbined outflows $\mathbf{r}_t$, storage volumes $\mathbf{s}_t$, spills $\mathbf{l}_t$, and irrigation withdrawals $\mathbf{i}_t$, as well as the vectors of marginal values of water $\boldsymbol{\lambda}_t$. These results are obtained after implementing the SDDP model in simulation (forward pass) by exploiting the last (updated) set of piecewise linear benefit-to-go functions F_t available at each stage t.

Simulated storage volumes in the four largest reservoirs (Keban, Karakaya, Ataturk, and Tabqa) are displayed in Fig. 5 where the points are the raw data, the band near the middle of the box is the mean storage volume, and the size of the box corresponds to one standard deviation from the mean (i.e., 68% confidence interval assuming that the storage volumes are normally distributed). It can be seen that the draw-down refill cycles in the two upstream reservoirs, Keban and Karakaya, are synchronized, reaching their maximum and minimum levels almost at the same time (respectively, in April and July). Further downstream, the Ataturk reservoir is operated at a more constant level with a maximum pool elevation reached in August, two months after the two upstream reservoirs. This delay can be explained by the fact that a significant portion of the Ataturk's inflows are actually the outflows from upstream Karakaya, which is refilled from May to July and then depleted from September onward. This delay is even more pronounced with the Lake Assad reservoir (Tabqa Dam) in Syria, which is slowly depleted until September and then quickly refilled as the outflows from the Ataturk reservoir increase. The fact that the evaporation losses at the Tabqa reservoir are significant during the low flow season, attributable to the combined effects of climate and reservoir geometry, is also a factor contributing to keeping storage levels low during summer months. From Fig. 5, it is clear that each reservoir exploits its storage capacity (although not entirely) to match supply with demand, therefore providing benefits to the system.

To assess the annual economic value of storage V_y^k in the kth hydrologic scenario, the following equation is used

$$V_y^k = \sum_{j=1}^{J} V_y^k(j) = \sum_{t=1}^{12}\sum_{j=1}^{J} \lambda_t^k(j)|\Delta s_t^k(j)| \tag{14}$$

where $\lambda_t^k(j)$ = marginal water value in the jth reservoir; and $\Delta s_t^k(j)$ = change in storage that occurs during month t in that reservoir.

As previously indicated, because the system is simulated over 40 different hydrologic scenarios, it is possible to derive a vector of 40 storage values $\mathbf{V}_y$. Moreover, the individual representation of each reservoir also allows the determination the contribution of each hydraulic infrastructure to the annual benefits of storage. Fig. 6 displays the cumulative distribution functions of the total economic value of storage and the contribution of the four largest reservoirs in

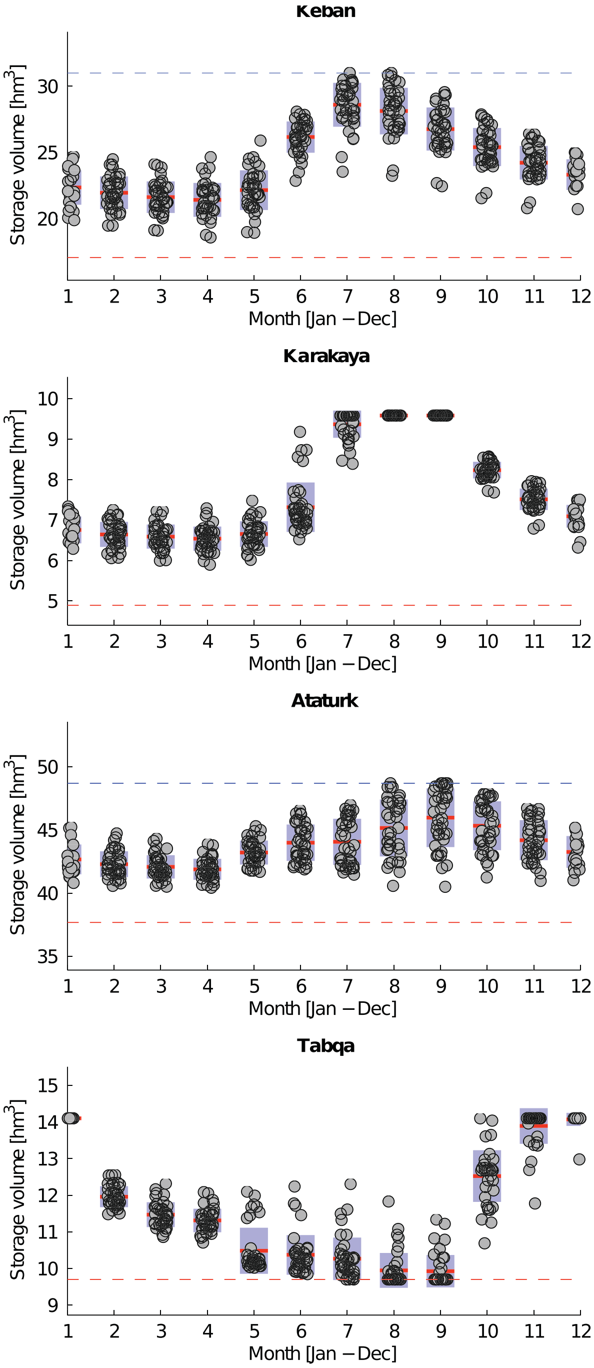

Fig. 5. Simulated storage volumes

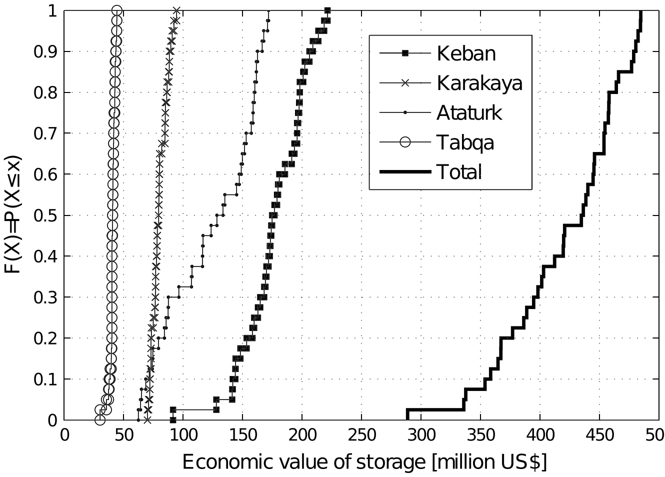

Fig. 6. Economic value of storage

Table 2. Value of Storage in the Four Largest Reservoirs

Name	$\bar{V}_y$ (million US$/year)	Coefficient of variation (%)	Ω (US$/1,000 m^3)
Keban	176	15	12.66
Karakaya	80	8	17.09
Ataturk	123	30	11.21
Tabqa	40	6	9.26

the system (Keban, Karakaya, Ataturk, and Tabqa). It can be seen that the average value of storage for the entire cascade of reservoirs is around 420 million US$/year, which is 18% of the annual short-run benefits of the system (2.26 billion US$/year). The minimum value can be as low as 300 million US$/year, whereas the maximum can reach 475 million US$/year, depending on the hydrologic conditions. This percentage is very similar to that calculated in the Zambezi River basin where a *with or without* analysis was implemented (Tilmant et al. 2012). Compared with the Zambezi study, the proposed approach is able to assess the individual contribution of each reservoir to the benefits of storage.

The analysis of simulation results reveals that the largest contributor is the Keban reservoir, which is the head reservoir with the largest live storage capacity and the largest natural inflows. The next most likely contributor is the Ataturk reservoir followed by Karakaya and then Tabqa. Table 2 lists the reservoirs, their average economic value of storage ($\hat{V}_y$), and the corresponding coefficient of variation (CV). The last column gives the average value of storage per unit storage capacity (Ω)

$$\Omega(j) = \frac{\hat{V}_y(j)}{\bar{s}(j) - \underline{s}(j)} \tag{15}$$

Clearly, the economic value of storage is proportional to the live storage capacity; the larger the storage capacity, the larger will be (1) the value attached to the ability to move water over time, and (2) the variability of the drawdown refill cycles. If the ratio Ω is fairly similar for Keban, Ataturk, and Tabqa, the situation is different at Karakaya because of a relatively large, efficient power station for a relatively small reservoir. This came as a surprise as one would expect the value of storage per unit storage capacity to decrease with the position with respect to the head reservoir (the inflows to the downstream reservoirs tend to be more regulated, therefore requiring less storage variations).

Fig. 7 shows (1) the statistical distribution of the contributions of these individual storages to the short-run annual benefits of the entire system, and (2) the cumulative upstream-downstream contributions. On average, Keban's contribution corresponds to 7.7% of the benefits, which is then followed by Ataturk (5.4%), Karakaya (3.5%), and Tabqa (1.8%). It can also be seen that the variability of the cumulative contributions increases as one moves downstream. At the end of the system (downstream of Tabqa), the cumulative contribution of the four reservoirs to the system-wide benefits varies from 12% to 24%; a variation twice as large as that observed for the first two reservoirs (Keban and Karakaya).

The previous results reveal that the value of storage changes according to the hydrologic scenarios used in the forward

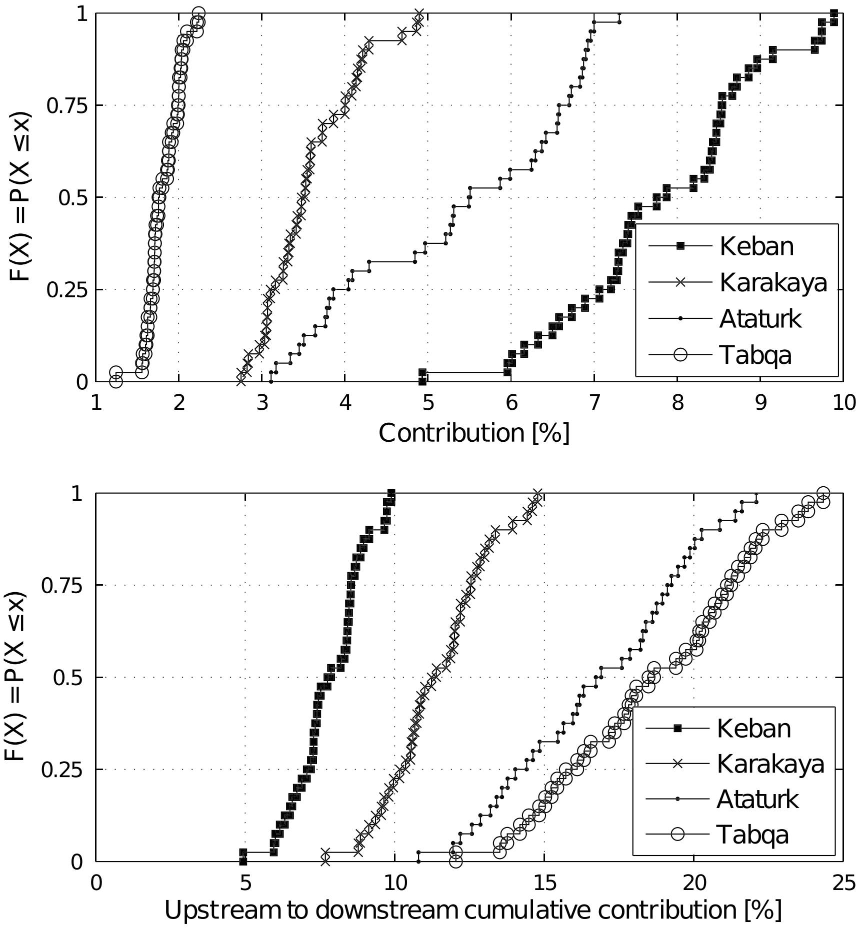

Fig. 7. Relative contributions to the system-wide benefits

simulation phase of the optimization algorithm. Dry hydrologic sequences tend to yield larger water values, whereby wet scenarios require extensive water transfers from the high flow to the low flow season. To identify the main hydrologic factors affecting the value of storage, a preliminary analysis is carried out for the Keban reservoir. Indicators characterizing the hydrologic scenarios are selected and then their degree of dependence with the value of storage in Keban $\mathbf{V}_y(j = 1)$ is measured using the Pearson's correlation coefficient. The indicators are

- The standard deviation (σ_q): This indicates how much dispersion exists in scenario k. One would expect the value of storage in a particular hydrologic scenario to increase with the variability in the scenario, because storage is used to attenuate fluctuations.
- The maximum flow ($q_{\max}$): A hydrologic scenario with a high peak flow is expected to increase the value of storage because more water must be stored for future uses.
- The annual discharge (q_{tot}): Because the hydrologic regime of the Euphrates in Turkey is characterized by two distinct seasons, the value of storage may depend on the annual discharge.
- The high flow season discharge (q_{hf}): Because 80% of the annual discharge takes place during the high flow season, the value of storage might depend on the sum of the flows of March, April, May, and June.

The measures of the linear dependence between the indicators and the value of storage are listed in Table 3. The best linear dependence is obtained with the standard deviation (σ_q) and the largest monthly discharge ($q_{\max}$).

Table 3. Hydrologic Indicators

Indicators	Correlation
σ_q	0.79
$q_{\max}$	0.76
q_{tot}	0.67
q_{hf}	0.62

Conclusions

The renewed impetus for large water storage infrastructure in developing countries and countries in transition poses numerous challenges to water managers and policy makers. One of the challenges is to effectively address the issues associated with the often large environmental and social costs associated with dams, which must be compared with the social benefits that the infrastructure is expected to bring in. Because many rivers are already dammed, it becomes increasingly relevant to be able to assess the individual contribution of the various dams to the value associated with storage (the ability to move water in time). This paper presents a methodology to determine the economic value of storage in multipurpose multireservoir systems and uses the cascade of reservoirs in the Euphrates River basin as a case study. By exploiting the results of a large-scale stochastic optimization model, the economic value associated with storage varations in each reservoir can be determined and their contribution to the system-wide benefits be assessed. In the absence of an analytical representation for the

J. Water Resour. Plann. Manage., 2014, 140(3): 375-383

marginal net benefit function for storage services, the economic value of storage over a given time period is approximated by the product of the change in storage and the change in marginal water value during that period. This approximation is only applicable if small changes in storage occur during that period. For this case study, the results reveal that (1) storage contributes to 18% of the annual benefits of the system and (2) the main factor affecting the contribution of a particular reservoir is its live storage capacity and the variability within a hydrologic scenario. However, the results are inconclusive as to whether the value of storage per unit storage capacity decreases with the position with respect to the head reservoir.

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II

Combining a partial and general equilibrium modeling approach to assess the economic impacts of the Grand Ethiopian Renaissance Dam on the Eastern Nile economies

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In Preparation

2012

Un cadre de modélisation joignant l'approche stochastique de programmation dynamique dual (SDDP) des niveaux de débit de base du bassin du Nil oriental et un modèle calculable global d'équilibre général (GTAP-W) est utilisé pour évaluer les impacts économiques à grande échelle du Grand Ethiopian Renaissance Dam (GERD) sur les économies du Nil oriental. La valeur ajoutée de cette approche par modélisation couplée est évaluée en comparant les résultats avec des modèles comparables d'équilibre partiel et un récent modèle CGE du GERD. Le modèle SDDP est utilisé pour résoudre le problème d'allocation de l'eau dans le bassin du Nil oriental avec GERD en ligne. Les changements apportés dans la répartition optimale de l'eau, la production agricole et la production d'énergie hydroélectrique provenant de SDDP sont ensuite mises en oeuvre dans le modèle CGE pour estimer les impacts économiques directs et indirects du barrage sur les pays du Nil oriental. Les résultats démontrent l'importance du GERD au niveau des retombées économiques à l'échelle du bassin. Avec le GERD opérant en amont, la croissance économique, les revenus et la consommation des ménages, de même que le bien-être des populations s'améliorent dans tous les pays du Nil oriental. Cependant, la répartition des bénéfices favorise principalement l'éthiopie et, dans une moindre mesure, le Soudan. Comme l'économie égyptienne est très sensible à l'approvisionnement énergétique, un commerce de l'électricité sur l'ensemble du bassin stimulerait sensiblement l'économie égyptienne, augmentant ainsi la valeur économique du barrage.

Combining a partial and general equilibrium modeling approach to assess the economic impacts of the Grand Ethiopian Renaissance Dam on the Eastern Nile economies[1]

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Abstract

A modeling framework that couples a bottom-up engineering-based stochastic dual dynamic programming (SDDP) approach of the Eastern Nile basin base level flows and a global Computable General Equilibrium model (GTAP-W) is used to estimate the economy-wide impacts of the Grand Ethiopian Renaissance Dam (GERD) on the Eastern Nile economies. The value-added of the coupled modeling approach is assessed by comparing model results with those from comparable partial equilibrium models and a recent CGE model of the GERD. The SDDP model is employed to solve the water allocation problem in the Eastern Nile basin with GERD online. The SDDP-derived changes in optimal water allocation, agricultural output and hydropower generation are subsequently implemented in the CGE model to estimate the direct and indirect economic impacts of the dam on the Eastern Nile countries. The results demonstrate the significance of the GERD in generating basin-wide economic benefits. With the GERD operating upstream, economic growth, household income and consumption expenditures and welfare improve in all the Eastern Nile countries. However, the distribution of benefits favors mainly Ethiopia and to a lesser extent Sudan. Since Egypt's economy is highly responsive to energy supply, instituting a basin-wide power trade scheme would substantially boost Egypt's economy and thereby further increase the economic value of the dam.

Key words: Computable General Equilibrium Modeling, Stochastic Dual Dynamic Programming, Grand Ethiopian Renaissance Dam, Eastern Nile Countries

1. Introduction

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[1] This chapter is based on a manuscript jointly authored with Diane Arjoon, her PhD supervisor at Laval University, Dr Amaury Tilmant, and my supervisors, submitted for review to the journal *Water Resources Research*.

Ethiopia is building a huge hydropower dam known as the Grand Ethiopian Renaissance Dam (GERD) on the Blue Nile River close to its border with Sudan. The dam constitutes the centerpiece of the country's five-year Growth and Transformation Plan (GTP) (2010/11-2014/15) that targets boosting the country's hydropower generating capacity from 2,000 MW in 2009/10 to 10,000 MW in 2014/15 (MoFED, 2010). The GERD is estimated to cost € 3.34 billion and will have a height of 145 meter and a total storage volume of 74 km^3. The dam, which is planned to be used for power generation only, has a design capacity of 6,000 MW and is reported to be able to produce 15.1 TWh/year upon completion (MDI, 2012). This would mean a massive additional energy source in the country and is expected to create enough supply to meet domestic as well as export demand for electricity.

The Blue Nile River constitutes the most important source of water supply in downstream countries Sudan and Egypt. The project has therefore been a source of concern for downstream countries. Ethiopia argues that the GERD will offer several benefits to these countries, including hydropower supply at a comparably cheaper price, flood control, water savings through reduced evaporation losses from downstream reservoirs and trapping silt. In order to create trust and consensus on sharing the dam's benefits, the Eastern Nile countries agreed on the establishment of an International Panel of Experts (IPoE), tasked with assessing the impact of the dam on downstream countries. The IPoE's report indicates, among other things, that the dam could potentially offer significant benefits to all the three Eastern Nile countries (MoFA, 2013). This corresponds with findings of recent studies on the dam (Kahsay et al., 2015; Arjoon et al., 2014) as well as earlier studies that assessed the downstream impact of a cascade of hydropower projects with a combined storage capacity comparable to that of the GERD on the Ethiopian part of the Blue Nile Basin (e.g. Guariso and Whittington, 1987; Whittington et al., 2005; Blackmore and Whittington, 2008; Goor et al., 2010; Block and Strzepek, 2010).

In the literature, the economic impacts of dams have been assessed using partial and general equilibrium modeling approaches. Several studies analyzed the economic effects of infrastructure development in the Blue Nile River in Ethiopia using partial equilibrium models (e.g. Jeuland, 2010a; Jeuland, 2010b; Whittington et al., 2005; Block and Strzepek, 2010; Goor et al., 2010). These studies are essentially deterministic. Only Goor et al. (2010) adopt a stochastic programming approach to assess the economic benefits and costs associated with new water storage infrastructures in the upper Blue Nile in Ethiopia. The findings of the study reveal that the construction of four mega dams (Karadobi, Beko-Abo, Mandaya and Border) in the Blue Nile Basin in Ethiopia would have tremendous positive impacts on hydropower generation and irrigation in Ethiopia and Sudan. Moreover, evaporation losses from the reservoir of the High Aswan Dam would be reduced substantially if operation of the reservoirs is coordinated. Similarly, a recent partial equilibrium analysis of the economic impact of the GERD presented by Arjoon et al. (2014) applies a stochastic dual dynamic programming (SDDP) approach to assess the impact of the operation of the dam on the Eastern Nile economies. Their findings reveal that water storage in the GERD would benefit downstream countries through improved irrigation and hydropower development and reduced hydrologic risks particularly during dry years.

Computable General Equilibrium (CGE) models are best-suited to analyze the direct as well as indirect impacts of dams (Robinsen et al., 2008). Yet, CGE analyses of water infrastructure are not that common and their scope is typically confined to national impacts of dam projects. Examples include Egypt’s High Aswan Dam (HAD) (Strzepek et al., 2008) and Australia’s Traveston dam (Wittwer, 2009). Employing a dynamic version of the GOBE_EN CGE model, Ferrari et al. (2013) conducted a preliminary assessment of the possible economic effects of the GERD on the Ethiopian economy. Their preliminary results indicate that the investment in the GERD would slow down economic development in Ethiopia while exports of hydro-electricity need to expand rapidly after dam completion for the investment to be profitable. This could in turn lead to what has been labelled “Dutch disease”, i.e. an increase in inflation and the exchange rate resulting in exports becoming more expensive and a negative effect on the trade balance due to more imports. A recent CGE study on the transboundary economic impacts of the GERD is reported by Kahsay et al. (2015). The authors used the GTAP-W model to evaluate the impact of the dam under three different climate and hydrological scenarios, taking into account both the transient impounding phase and the long-term operation phase of the dam. The results demonstrate the significance of the GERD in generating basin-wide economic benefits and improving welfare in the Eastern Nile basin.

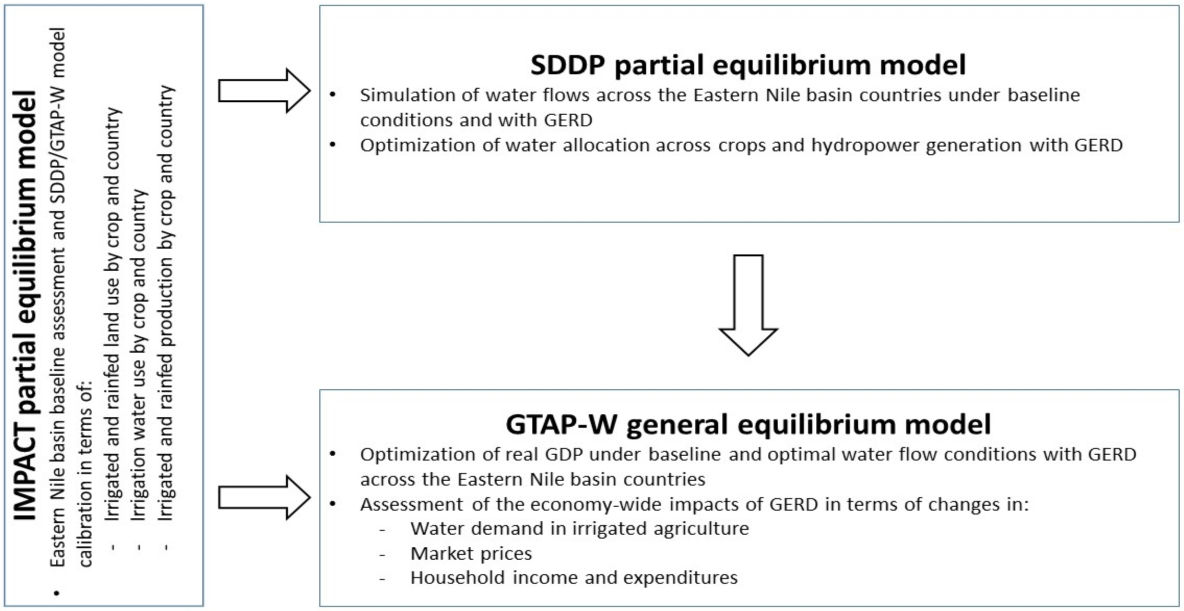
In this paper, we use a combination of the bottom-up engineering and SDDP-based water allocation model of the Eastern Nile basin (Arjoon et al., 2014) and the GTAP-W global CGE model (Calzadilla et al., 2010) to evaluate the transboundary economic impact of the GERD on the Eastern Nile economies. The former is a dynamic optimization model that contains vital hydrological details essential for analyzing water management for agricultural production and hydropower generation, but lacks relevant economic feedbacks due to its partial equilibrium nature. The CGE model, on the other hand, considers the entire economy as a complete, interdependent system and provides an economy-wide perspective. However, CGE models are highly aggregated and their results fail to shed light on relevant hydrological details (Brouwer and Hofkes, 2008). Moreover, CGE models are often criticized as being insufficiently validated and often relying on parameters that are not econometrically estimated (Beckman et al., 2011). The coupling of the two models applied in this study enriches the CGE model with hydrologic detail and the SDDP model with economic rigor. Moreover, the CGE model is fed in this case by the outcome of a dynamic optimization model. Typically, CGE models rely on simulations driven by exogenous 'shocks', which are not necessarily optimal. The synthesis of the two modeling approaches is thus expected to improve the validity and reliability of the CGE model. The outcome of the coupled partial and general equilibrium model is compared to the same model results based on a partial equilibrium and computable general equilibrium modeling approach.

The remainder of the paper is organized as follows. The next section presents the integrated modeling framework. Section 3 discuses the simulation results and section 4 concludes.

2. Integrated hydro-economic modeling framework

The modeling framework applied for the study combines the engineering-based SDDP model of the Eastern Nile basin countries (Arjoon et al., 2014) and the global CGE model (GTAP-W) (Calzadilla et al., 2010) using the GTAP Africa database for the Nile basin countries. The coupled modeling framework is presented in Figure 1. The two models are coupled in the sense that output of the former (optimal water allocation across crop production and electricity generation) is used as input in the latter (water endowments) to estimate the economy-wide impacts of the GERD on the Eastern Nile economies.

Figure 1: Overview of the integrated hydro-economic modelling framework



IMPACT partial equilibrium model

- Eastern Nile basin baseline assessment and SDDP/GTAP-W model calibration in terms of:
  - Irrigated and rainfed land use by crop and country
  - Irrigation water use by crop and country
  - Irrigated and rainfed production by crop and country

SDDP partial equilibrium model

- Simulation of water flows across the Eastern Nile basin countries under baseline conditions and with GERD
- Optimization of water allocation across crops and hydropower generation with GERD

GTAP-W general equilibrium model

- Optimization of real GDP under baseline and optimal water flow conditions with GERD across the Eastern Nile basin countries
- Assessment of the economy-wide impacts of GERD in terms of changes in:
  - Water demand in irrigated agriculture
  - Market prices
  - Household income and expenditures

The strength of the partial equilibrium SDDP model lies in its ability to incorporate detailed information on the hydraulic infrastructure and the stochastic hydrologic processes. The model contains relevant details concerning land and water use, crop production and hydropower generation at power plant level. It also includes water balance equations at each node of the system (Figure 2). However, the partial equilibrium nature of the model means that the analysis of the water management problem is limited to certain sectors (agriculture and hydropower) only and confined to the hydrological area located within the Nile basin area of each country. The model hence does not provide insights into the effects of developments in the hydrological areas on the rest of the economy and vice versa. The model depicts only part of the overall economy and assumes that there exist no inter-sectoral linkages and relevant economic feedbacks. This seems unlikely given the central role of food and energy production in developing economies. Moreover, partial equilibrium models are incomplete in the sense that they fail to capture the potentially important relationships between prices and quantities (Dixon *et al*., 2005). Prices are treated as exogenous while in practice changes in outputs are expected to affect product prices and changes in input demands could well be reflected in input prices.

A general equilibrium perspective provides insights into the economy-wide impacts of water resources policy. Unlike partial equilibrium models which analyze the different sectors separately under *ceteris paribus* assumptions, the general equilibrium approach accounts for various inter-linkages between economic sectors to analyze economy-wide effects that could occur as a consequence of a policy change. Moreover, CGE models determine relative product and factor prices endogenously so that product and factor markets attain their equilibrium through the adjustment of prices. However, unlike partial equilibrium models, CGE models are highly aggregated and lack relevant hydrological details needed to assess the optimal spatial allocation of water and land resources across crops at agricultural plot level and hydropower generation at plant level. The coupling of the two modeling approaches allows exploiting their respective attributes and complementary capabilities. Their interaction increases the necessary solid hydrological foundation for the assessment of the economy-wide impacts of the GERD. It enables capturing interactions between water and energy-dependent sectors and links the hydrological areas to the rest of the economy and hence provides a rich set of economic feedbacks and a complete assessment of the welfare effects of the GERD. The coupling of the two models is thus expected to improve the validity and reliability of the CGE model.

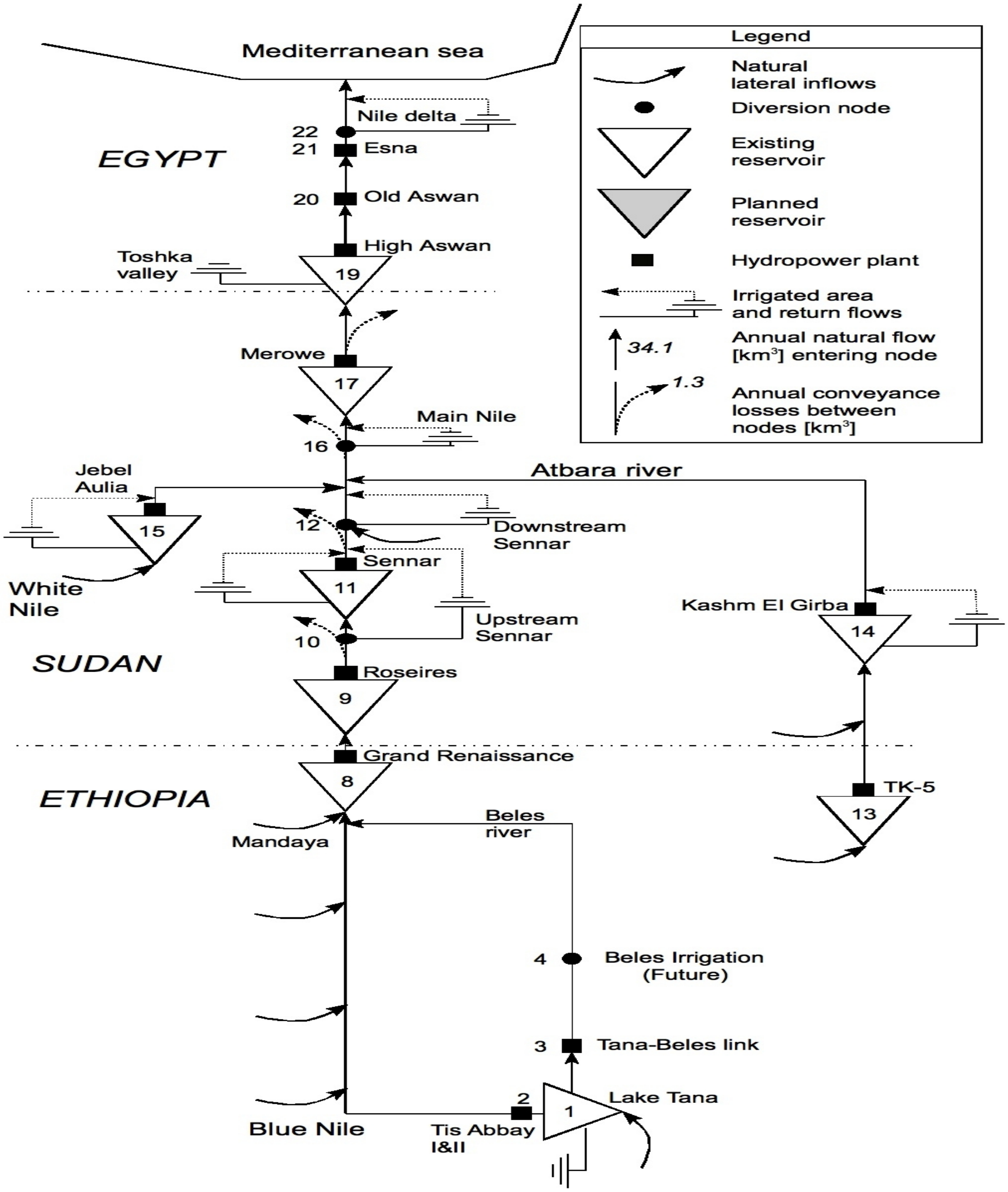
To ensure that both models start from the same baseline conditions in the Nile basin and apply the same crop yield functions, detailed data on land and water use as well as crop yields specified per country from the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) developed at the International Food Policy Research Institute (IFPRI) are used to calibrate and benchmark the baseline of the SDDP and GTAP-W model. IMPACT is a partial equilibrium model of agricultural demand, production and trade that covers the major agricultural commodities produced in the world at individual country level (Rosegrant et al., 2005). The IMPACT model provides detailed baseline data for the year 2000 with respect to irrigation water use, crop yields and cropped area, distinguishing between 20 rainfed and irrigated crops and 281 food processing units for 115 economies and 126 river basins. Short descriptions of the SDDP and GTAP-W models follow below.

2.1 The SDDP model

The SDDP model is an integrated hydro-economic model of the Eastern Nile countries that accounts for the interaction between essential hydrologic, economic and institutional components. The model is a dynamic optimization model formulated to maximize the expected aggregate net benefits associated with water use for agricultural production and hydropower generation in the Eastern Nile countries over a given planning period, taking into account the main hydraulic infrastructure and water demands. Unlike most deterministic hydro-economic models (e.g. Rosegrant et al., 2000; Booker et al., 2005; Whittington et al., 2005, Wang et al., 2008; Ward and Pulido-Velazquez, 2008), the SDDP approach considers the effect of hydrologic uncertainty on allocation policies and incorporates the notion of risk in the analysis through the inclusion of statistical distributions related to positive and negative externalities such as benefits related to flood control, reduced sediment load and regulated flow and potential adverse effects on agricultural production and power generation in downstream countries due to GERD. The model has been used in several studies to analyze multipurpose and multi-reservoir water management problems with stochastic inflows. For example, to determine the economic value of water storage in the Euphrates River basin (Tilmant et al., 2014), to examine the cost of non-cooperation in the Zambezi River basin (Tilmant and Kinzelbach, 2012), and to assess the economic value of coordination in a large-scale, multi-reservoir system in the Parana River (Marques and Tilmant, 2013).

The SDDP model of the Eastern Nile Basin includes 9 irrigation demand sites and 12 hydropower plants located in the three Eastern Nile countries: 1 irrigation site and 4 hydropower plants in Ethiopia, 6 irrigation sites and 5 hydropower plants in Sudan, and 2 irrigation sites and 3 hydropower plants in Egypt. Figure 2 depicts the schematic overview of the nodes comprised of all major reservoirs, hydropower plants and irrigation schemes as well as the river reaches considered in the model. The model solves the water resources allocation problem using monthly time steps. To deal with the multi-year storage capacity of some of the reservoirs, a planning horizon of 10 years (T=120 months) is used. See Arjoon et al. (2014) for more details on the SDDP model of the Eastern Nile River basin.

Figure 2: Schematic overview of the Eastern Nile Basin in the SDDP model



2.2 The GTAP-W model

The CGE model applied in this study is the Global Trade Analysis Project (GTAP) model (Hertel, 1997), developed at Purdue University, USA. GTAP provides a global modeling framework and a common global database, providing the opportunity to conduct comparable model implementations and policy simulations. GTAP is a static-comparative, multi-region, multi-sector CGE model of the world economy that examines all major aspects of an economy via its general equilibrium feature. The GTAP model comprises accounting relationships, behavioral equations and global sectors required to complete the model. The accounting relationships of the model ensure the balance of receipts and expenditures for every agent identified in the economy, whereas the behavioral equations specify the behavior of optimizing agents in the economy on the supply and demand side based on microeconomic theory (Brockmeier, 2001). The production system is set up as a series of nested constant elasticities of substitution (CES) functions combined through substitution elasticities (see Figure 3). The analysis presented here uses the version of the GTAP-W model (Calzadilla et al., 2010) that distinguishes between rainfed and irrigated agriculture and implements water as a factor of production directly substitutable in the production process of irrigated agriculture.

Following Calzadilla *et al*. (2011), the agricultural land endowment in the standard GTAP database is disaggregated into rainfed land, irrigable land, and irrigation water based on data generated by the IMPACT model. The relative share of rainfed and irrigated agriculture in total production is used to split the land rent in the original GTAP database into a value for rainfed land and a value for irrigated land for each crop in each region. In a next step, the ratio of irrigated yield to rainfed yield is used to split the value of irrigated land into a value for irrigated land and irrigation water. Due to a lack of data, the values for the elasticity of substitution between irrigated land and irrigation water used in this study are adapted from Calzadilla et al. (2011) and vary between 0.05 in Ethiopia and Sudan and 0.08 in Egypt. Sensitivity analysis of model results with respect to these elasticity parameters is conducted in Kahsay et al. (2015) to test the sensitivity of the results to alternative values of the parameters.

Figure 3: GTAP-W nested production structure

Source: Calzadilla et al. (2010).

Explanatory notes:
σ is the constant elasticity of substitution (CES) between value added and intermediate inputs.
σVAE: CES between primary factors.
σLW: CES between irrigated land and irrigation water.
σKE: CES between capital and energy composite.
σD: CES between domestic and imported inputs.
σM: CES between imported inputs.

For the purpose of the present study, the GTAP Africa Data Base is aggregated into seven regions: Ethiopia, Sudan including South Sudan, Egypt, the Equatorial Lakes (EQL) region, Rest of North Africa, Rest of Sub-Sahara Africa and Rest of the World (ROW). Since the focus of the study is exclusively on the Eastern Nile region that is directly affected by the GERD, the regional aggregation highlights the importance of the three Eastern Nile countries (see Appendix A). The 57 sectors in the GTAP Africa Data Base are aggregated for the purpose of this study into 17 sectors, of which 8 are agricultural sectors and 9 non-agricultural sectors (see Appendix B).

3. Simulation results

3.1 Simulation results based on the SDDP model

In estimating the economic impact of the GERD on the Eastern Nile economies, the potential impact of GERD operation on irrigation water supply, agricultural production, hydropower generation, irrigation water use efficiency and capital stocks are considered. The SDDP model is employed to identify changes in crop production, hydropower generation and irrigation water supply in the Eastern Nile countries due to GERD operation (Table 1).

The GERD is not expected to entail a reduction of water flowing downstream. Since hydropower production is a non-extractive water related activity, the flow of the Nile would not be diminished once the reservoir is filled and the GERD goes operational. The flow of the Nile is thus expected to be non-declining with the GERD operating upstream. Accordingly, the SDDP model results reveal that water supply and hence crop production remains unchanged in Egypt and more or less stable in Ethiopia, while Sudan would gain substantial improvements in irrigation water use and hence crop production with GERD operating upstream (Table 1). The GERD will create a regulated flow in the Blue Nile River and the main Nile River, and as a result will offer a more constant flow over the whole year for irrigated agriculture in Sudan and Egypt. This would ensure a more continuous irrigation water supply and improved water use efficiency than is the case without the GERD. Following Kahsay et al. (2015), GERD operation is assumed to result in a 5 percent improvement in water use efficiency in Sudan and Egypt. We only assume an increase in water use efficiency in irrigated agriculture in Sudan and Egypt, not in Ethiopia, because irrigated agriculture is still very limited in Ethiopia (Tesfaye et al., 2016). Based on the assessment of Blackmore and Whittington (2008) regarding the impact of increased water storage in Ethiopia, we assume a 3.4 percent gain in irrigation water supply downstream in Egypt due to GERD operation.

Table 1: Estimated percentage change in irrigation water allocation across crops and optimal crop output due to GERD based on the SDDP model

	Change in irrigation water use					**Change in irrigated land use**					**Change in crop output**				
	Egypt	Ethiopia		Sudan		Egypt	Ethiopia		Sudan		Egypt	Ethiopia		Sudan	
		km^3/yr	%	km^3/yr	%		hectares	%	hectares	%		tons/yr	%	tons/yr	%
Rice	0.0	0.0	0.0	0.002	3.5	0.0	0.0	0.0	108	3.5	0.0	0.0	0.0	105	3.5
Wheat	0.0	0.0	0.0	0.003	0.3	0.0	0.0	0.0	205	0.3	0.0	0.0	0.0	469	0.3
Other cereals	0.0	0.0	0.0	2.363	29.5	0.0	0.0	0.0	336,231	29.5	0.0	0.0	0.0	157,437	23.4
Other crops	0.0	0.0	0.0	0.160	47.8	0.0	0.0	0.0	22,912	47.8	0.0	0.0	0.0	9,784	47.8
Fruits & vegetables	0.0	-0.0005	-0.8	0.002	0.1	0.0	-59	-0.3	158	0.1	0.0	-365	-0.4	646	0.0
Oilseeds	0.0	0.0	0.0	0.009	0.3	0.0	0.0	0.0	1,312	0.3	0.0	0.0	0.0	1,096	0.3
Sugar cane, Sugar beet	0.0	0.0	0.0	0.030	1.9	0.0	0.0	0.0	660	1.9	0.0	0.0	0.0	58,148	1.9
Total	0.0	-0.0005	-0.3	2.568	16.5	0.0	-59	-0.1	361,585	18.7	0.0	-365		227,683	

The SDDP model results reveal that the GERD will substantially boost the energy generation in the Eastern Nile countries. With GERD online, hydropower generation in Ethiopia and Sudan will increase by 505 and 6 percent respectively, while Egypt would see no change in the status quo (Table 2). The electricity sector in the standard GTAP database is an aggregate of different power generation activities. Although the Eastern Nile basin countries derive electricity from different sources, the model has only one electricity sector. Therefore, the change in hydropower supply due to the GERD is simulated as a percentage change in the total supply of electricity. Available data shows regional variation in the source of electric power generation in the Eastern Nile Basin countries. Ethiopia and Sudan rely on hydropower for as much as 99 and 75 percent of their electric power supply, respectively, while Egypt heavily relies on natural gas and derives less than 10 percent of its electricity from hydropower (Table 2). As shown in Table 2, the change in hydropower supply resulting from GERD operation and the relative share of hydropower in total electricity production in these countries is used to induce the required policy intervention in the electricity sector.

Table 2: The expected impact of GERD on hydropower generation and overall electricity production based on the SDDP model

	Hydropower generation			**Share of hydropower in electricity production* (%)**	**Change in electricity generation due to GERD (%)**
	Without GERD (TWh/yr)	With GERD (TWh/yr)	Change (%)		
Egypt	10.77	10.69	-0.7	8.3	-0.1
Ethiopia	2.42	14.79	510.2	99.0	505.1
Sudan	5.39	5.84	8.5	75.2	6.4

* Source: World Development Indicators (2013).

Moreover, the construction of the GERD is expected to increase Ethiopia's capital stock by about 10 percent (Kahsay et al., 2015). Table 3 presents the simulation scenarios considered for the GTAP-W model implementation, the results of which are presented in the next section.

Table 3: Simulation scenarios in the Eastern Nile basin countries for the GTAP-W model derived from the SDDP modeling approach (% change from the baseline conditions)

	Egypt	Ethiopia	Sudan
Electricity supply	-0.1	505.1	6.4
Irrigation water use	3.4	-0.3	16.5
Irrigated land use	0.0	-0.1	18.7
Crop output			
Rice	0.0	0.0	3.5
Wheat	0.0	0.0	0.3
Other cereals	0.0	0.0	23.4
Other crops	0.0	0.0	47.8
Fruits & vegetables	0.0	-0.4	0.0
Oilseeds	0.0	0.0	0.3
Sugar cane, Sugar beet	0.0	0.0	1.9
Water use efficiency	5.0	0.0	5.0
Capital stock	0.0	10.0	0.0
Domestic saving	0.0	10.0	0.0

3.2 Simulation results based on the GTAP-W model

This section presents the results of the simulations based on GTAP-W to assess the direct and indirect economic effects of GERD operation on the Eastern Nile economies. We use changes in real GDP, market prices of agricultural produce, irrigation water demand across crops, household income and consumption expenditures and overall welfare effects relative to the baseline situation as indicators of the economic effects of the dam.

The GERD is expected to result in water savings in the Eastern Nile that would benefit Sudan and Egypt. The simulation results shown in Figure 4 testify this. Water use in irrigated agriculture increases considerably in the agricultural sectors in Egypt and Sudan. In Egypt, irrigation water use is expected to increase 1.5 to 5 percent in all agricultural sectors. The expected rise in irrigation water use in Sudan is much more prominent than in Egypt. Irrigation water use increases 16 to 41 percent in Sudan’s agricultural sectors except for cereals where water use falls by 38 percent. In Ethiopia, the demand for irrigation water is expected to increase 2 to 3.5 percent except for other grains and crops and oil seeds where water use falls by 5 and 3 percent, respectively. Water use remains more or less stable in the Ethiopian rice sector.

Figure 4: The predicted percentage change in water demand in irrigated agriculture in the Eastern Nile countries due to GERD operation relative to the baseline year 2000 based on GTAP-W

The decline in water use in Sudan’s other cereals sector is small in absolute terms. The share of the sector in the country’s total irrigation water use was 3.5% in the baseline situation and declines to 2% after the simulation of the impacts of GERD implementation.

The changes in agricultural output due to GERD derived from the SDDP model and implemented in the CGE model as input variables are expected to influence market prices of crops. The simulation results in Figure 5 show a fall in agricultural prices in Egypt and Sudan. In Egypt prices decrease in all agricultural sectors by 0.1 to almost 4 percent. Agricultural prices fall in Sudan’s agricultural sectors except in wheat, vegetables and fruits and sugar where prices increase between 0.1 and 3 percent. Due to the substantial increase in irrigation water use and hence improvements in agricultural production, the GERD induces a substantial decline in agricultural prices (0.2-64%) in the remaining agricultural sectors in Sudan. The notable decline in the price of other cereals and other crops is explained by the substantial increase in the output of these products. In Ethiopia, crop prices rise between 2.1 and 6 percent in all agricultural sectors.

Figure 5: The predicted percentage change in the price of agricultural products in the Eastern Nile countries due to GERD operation relative to the baseline year 2000 based on GTAP-W

Table 4 presents the effect of the GERD on real GDP and real return to unskilled labor. The simulation results demonstrate that the dam results in a higher level of real output and hence positive growth for all the Eastern Nile countries. Although all the Eastern Nile countries experience economic growth due to the GERD, the distribution of benefits favor mainly Ethiopia and to a lesser extent Sudan. The basin-wide gain in real GDP due to the GERD relative to the baseline situation is about USD 2.26 billion in 2000 prices. Ethiopia and Sudan gain much more (USD 1.65 and USD 0.55 billion respectively) compared to Egypt (USD 0.064 billion). The gains in real GDP correspond to an economic growth rate of 0.1, 10.4 and 3.3 percent in Egypt, Ethiopia and Sudan, respectively compared to the baseline.

The economic growth the Eastern Nile countries experience due to the GERD tends to be pro-poor in the sense that it improves the real return for unskilled labor in these countries. The real return to unskilled labor measures the change in return to unskilled labor relative to the price index of household consumption expenditures and hence reflects trends in poverty reduction. Real return for unskilled labor improves in all the Eastern Nile countries (Table 4). Thus, the GERD is of significant importance in reducing poverty, mainly in Ethiopia and Sudan and to a lesser extent in Egypt.

Table 4: The predicted effect of GERD operation on real GDP and real return to unskilled labor relative to the baseline year 2000 based on GTAP-W

	Real GDP		**Return to unskilled labor**
Regions	%	US$ million/yr	%
Egypt	0.1	64	0.2
Ethiopia	10.4	1649	8.6
Sudan (pre-2011)	3.3	549	1.5
Total		2,262	

The simulation results for household income and expenditures are depicted in Figure 6. The results reveal that Ethiopia, followed by Sudan, enjoys the largest improvement in household income and hence consumption expenditures induced by GERD operation (8.3 and 4.2 percent, respectively). Egypt faces a slight decline in household income and consumption expenditures (0.3%).

Figure 6: Predicted percent change in household income and consumption expenditures in the Eastern Nile basin countries relative to the baseline year 2000 based on GTAP-W

The overall welfare effects of the GERD, as measured by the equivalent variation (EV), i.e. the amount of income that would have to be given to an economy before building the dam so as to leave the economy as well off as it would be after the dam has been built, are substantial (Figure 7). The total welfare gain and its distribution in the Eastern Nile countries due to GERD are more or less similar to that of real GDP. The results reveal that Egypt's economy is more responsive to a change in energy supply than water supply. For example, a one percent decline in hydroelectric supply results in a US$116.3 million welfare loss, while a one percent increase in water supply results in an almost 10 times smaller welfare gain of US$12.6 million. Thus, it appears that Egypt's economy is more constrained by energy supply than water availability. The results based on a welfare decomposition analysis (Huff and Hertel, 2000) reveal that the endowment effect (i.e. increase in water stocks and built infrastructure) and technical change contribute most to the welfare gain in Ethiopia and Sudan. Welfare gains in Egypt emanate from allocative efficiency, the endowment effect and technical change.

Figure 7: Expected welfare effects of the GERD in the Eastern Nile countries relative to the baseline year 2000 based on GTAP-W

3.3 Comparison of alternative modeling approaches

The results of the coupled modeling approach employed in this study are compared to that of two partial equilibrium (PE) and one computable general equilibrium (GE) modeling approach in the literature to estimate the net benefits of the GERD with a view to illustrate its value-added (Table 5).

Results from all models show substantial positive economic benefits for the Eastern Nile countries. However, differences in the magnitude of the estimated economic benefits can be observed across the modeling approaches. The differences between the results for the combined economic benefits of Sudan and Egypt reported in Arjoon et al. (2014) and Whittington et al. (2005) arise from differences in input data, assumptions and modeling approaches.

Whittington et al. (2005) developed a static deterministic (perfect foresight) hydro-economic model for the Nile River Basin to analyze the economic benefits of several development scenarios, including partial development of four mega dams (Karadobi, Mabil, Mendaia, and Border) proposed by the U.S. Bureau of Reclamation (USBR) in the Ethiopian part of the Blue Nile Basin (Lake Tana, Mabil, Border). The results of this study is assumed to be comparable since the partial development scenario of the Ethiopian Blue Nile does not allow agricultural water withdrawal, while enabling the country to generate 16.8 TWh/year in terms of energy, which is comparable to the GERD. Whittington et al. (2005) assume that the partial development of the Blue Nile Basin in Ethiopia would lead to a 15.7 km^3 decline in Egypt's water supply, resulting in a substantial negative economic benefit for the country, also when combined with the economic benefit for Sudan. The dynamic model developed by Arjoon et al. (2014) accounts for hydrological uncertainty and demonstrates that the GERD does not pose any threat to water supply in Egypt. Ensuring a constant water supply to Sudan and Egypt thereby yields positive economic benefits for both countries. Consistent with expectations, the resulting economic benefits based on the PE models are found to be less than those from the CGE and coupled PE-CGE model. Due to their comprehensive analytical power and economy-wide feedback, the CGE and coupled PE-CGE models are expected to provide a more complete assessment of the net economic benefits involved.

Table 5: Comparison of the expected net benefits of the Grand Ethiopian Renaissance Dam based on existing partial and general equilibrium modeling approaches

	Economic benefits (10^6 US$)				**Real GDP (% change)**		
	Ethiopia	Sudan	Egypt	Total	Ethiopia	Sudan	Egypt
Results from partial equilibrium models							
- Whittington et al. (2005)	1295	607	-951	951			
- Arjoon et al. (2014)				700[1]			
Results from the GTAP-W model							
- Kahsay et al. (2015)	1347	265	429	2041	8.8	1.6	0.3
Results from coupled SDDP and GTAP-W model							
- This study	1652	677	94	2423	10.4	4.2	0.1

[1] Combined net benefits for Sudan and Egypt due to GERD during dry hydrological conditions.

4. Discussion and conclusions

The results of our analysis reveal that the GERD generates substantial economic benefits and enhances economic growth and welfare in all the Eastern Nile countries. Although all the Eastern Nile countries gain from the GERD, the distribution of benefits favor mainly Ethiopia and to a lesser extent Sudan. The GERD also generates benefits in terms of lower market prices of agricultural products, increased household income and consumption expenditures. Moreover, the dam improves the real return to unskilled labor and hence contributes to poverty alleviation in the basin. The overall results of the study are consistent with the findings of previous studies (Strzepek et al., 2008; Aydin, 2010). This includes the findings of several hydro-economic models developed to evaluate the downstream impacts of Ethiopia's development of the Blue Nile waters to maximize hydropower production (e.g. Guariso and Whittington, 1987; Whittington et al., 2005; Blackmore and Whittington, 2008). Moreover, the results of this study corroborate a recent study by Kahsay et al. (2015). The findings of the study presented here reveal, like previous studies, that hydropower dams enhance economic growth and improve welfare. Only the findings by Ferrari et al. (2013) seem to indicate that the GERD investment would slow down economic development in Ethiopia, among others due to the risk of 'Dutch disease'. The coupled modeling approach applied in this study combines the strengths of partial and general equilibrium models and hence provides a methodological advantage over previous modeling approaches in that water allocation is first optimized in a more realistic bottom-up hydro-economic engineering model and these results are subsequently used to assess the wider direct and indoirect impacts of the GERD on the Eastern Nile economies. This coupled approach is expected to make the results more valid and reliable.

The results of the SDDP model employed to design the simulation scenarios for the GTAP-W model are similar, but not identical to those reported in other studies (Goor et al., 2010; Arjoon et al., 2014). The differences are mainly due to changes to the baseline and input data in the agricultural sector, which were made consistent in this study with the data used for the CGE model based on the IMPACT model. Besides, the SDDP results used in this study, like the stated studies, reveal that irrigation water use increases in Sudan and remains more or less unchanged in Egypt and Ethiopia. The increase in water supply in Egypt is exogenously implemented in this study to account for the net gain from reduced evaporation losses from the HAD due to GERD operation. While the SDDP model provides statistical distributions of performance indicators and allocation decisions, only the average values were used in this study to parameterize the GTAP-W model. It was beyond the scope of this study to carry out the same analysis for other percentiles representing dryer or wetter conditions. The SDDP model was also implemented assuming full cooperation among riparian countries. This assumption will be relaxed in future work to assess the direct and indirect benefits of transboundary cooperation in the Eastern Nile River basin using the proposed PE-CGE approach.

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Appendix A: Regional aggregation based on the GTAP Africa database

Region	Description
Ethiopia	Ethiopia

Sudan (pre-2011)	Sudan, including South Sudan
Egypt	Egypt
Equatorial Lakes Region	Democratic Republic of Congo (DRC), Uganda, Kenya, United Republic of Tanzania
Rest of North Africa (Rnf)	Morocco, Tunisia, Rest of North Africa
Rest of Sub-Sahara Africa	Cote d'Ivoire, Senegal, Rest of WAEMU, Ghana, Nigeria, Rest of ECOWAS, Cameroon, Rest of CAEMC, Rest of SADC, Rest of COMESA, Botswana, South Africa, Rest of South African CU, Madagascar, Malawi, Mauritius, Mozambique, Zambia, Zimbabwe, Rest of Sub-Saharan Africa
Rest of the World	Oceania, East Asia, Southeast Asia, South Asia, North America, Latin America, European Union 25, Rest of Europe, Middle East,

WAEMU: West African Economic and Monetary Union
ECOWAS: Economic Community of West African States
CAEMC: Central African Economic and Monetary Community
SADC: South African Development Community
COMESA: Common Market for Eastern and Southern Africa
CU: Customs Union

Appendix B: Sectoral aggregation based on the GTAP Africa database

Sector	Detail Description
I. Agricultural Sectors	
Paddy	paddy
Wheat	wheat
Cereal	Cereal grains not elsewhere classified (nec),
Other crops	Plant-based fibers; crops nec; processed rice,
Vegetables and fruits	Vegetables, fruit, nuts
Oilseeds	Oil seeds
Sugar	Sugar cane, sugar beet
Livestock and meat products	Cattle, sheep, goats, horses; animal products nec; raw milk; wool, silk-worm, cocoons; meat: cattle, sheep, goats, horses; meat products nec;
II. Non-agricultural sectors	
Coal	Coal
Crude	Oil
Gas	Gas; gas manufacturing, distribution
Petroleum	Petroleum, coal products
Electricity	Electricity
Processed food	Vegetable oils and fats; dairy products; sugar; food products nec; beverages and tobacco products
Extraction and manufacturing	Forestry; fishing; minerals nec; textiles; wearing apparel; leather products; wood products; paper

	products, publishing; chemical, rubber, plastic prods; mineral products nec; ferrous metals; metals nec; metal products; motor vehicles and parts; transport equipment nec; electronic equipment; machinery and equipment nec; manufactures nec;
Water	Water
Services	Construction; trade; transport nec; sea transport; air transport; communication; financial services nec; insurance; business services nec; recreation and other services; public administration, defense, health, education; dwellings

Explanatory note: nec means ‘not elsewhere classified’.

Appendix C

SDDP - Solving the hydro-economic model

The equations presented in Section 2.2.1 are the core of the reservoir operation model used in the studies. This model was solved using the stochastic dual dynamic programming (SDDP) method presented below. The next section briefly describes the stochastic dynamic programming (SDP) upon which SDDP is based, followed by a detailed description of SDDP.

C.1 Multistage decision-making problem

The optimal operation of a multi-reservoir system can be considered as a multistage decision-making problem. A sequence of T release decisions r_t must be determined so that the overall expected benefit Z is maximized:

$$Z = \left[\sum_{t}^{T} f_t(w_t, r_t, q_t) + \nu(w_{T+1}) \right] \tag{C.1}$$

where f_t is the immediate benefit of system operation during period t, q_t is the vector of inflows to the reservoirs during period t, w_t is the state vector describing the system's status at the beginning of period t, r_t is the vector of release decisions during period t, and $\nu(w_{T+1})$ is a terminal value function. In many reservoir operation problems the state vector includes a storage state variable s_t and a hydrologic state variable such as the previous flow q_{t-1}.

In a hydropower system, a typical immediate benefit function includes the net benefits from hydropower as well as penalty costs for not meeting target water demands and/or violating operating constraints:

$$f_t(s_t, r_t, q_t) = \tau_t \sum_j (\pi_t^h(j) - \theta(j))e(j)r_t(j)h_t(j) - \xi_t' x_t \tag{C.2}$$

where π_t^h is the energy price at time t for the j_{th} hydropower plant [\$/MWh]; $\theta(j)$ is the operation and maintenance cost of the jth hydropower plant [\$/MWh]; τ_t is the number of hours in period t; $e(j)$ is the efficiency function associated with the jth hydropower plant, which depends on the net head $h_t(j)$ and the release $r_t(j)$ [MW/m.m^{3}s^{-1}]; ξ is the vector of penalty coefficients [\$/unit deficit or surplus]; x_t is the vector of deficits or surpluses [unit deficit or surplus]. Irrigation rationing and/or the inability to meet minimum flow requirements are examples of deficits. Surpluses like unsafe storage levels for flood control purposes and/or spillages losses may also be penalized.

C.2 Stochastic dynamic programming

In stochastic dynamic programming (SDP) reservoir release decisions are made to maximize current benefits plus the expected benefits from future operation, which are represented by the recursively calculated benefit-to-go function F_{t+1}. Considering the reservoir operation problem as periodic with an infinite-horizon, the long-term optimal operating policy can be found through the recursive solution of the functional SDP equation:

$$F_t(s_t, q_{t-1}) = \underset{q_t|q_{t-1}}{E}[max\{f_t(s_t, q_t, r_t) + F_{t+1}(s_{t+1}, q_t)\}] \tag{C.3}$$

subject to

$$s_{t+1} - C_R(r_t + l_t) = s_t + q_t - e_t(s_t) - i_t \tag{C.4}$$

$$\underline{s}_{t+1} \leq s_{t+1} \leq \overline{s}_{t+1} \tag{C.5}$$

$$\underline{r}_t \leq r_t \leq \overline{r}_t \tag{C.6}$$

where l_t is the vector of spills, C_R is the system connectivity matrix, e_t is the vector of evaporation losses, i_t is the vector of irrigation water withdrawals, $\underline{s}$ and $\overline{s}$ are vectors with the minimum and maximum storage volumes respectively, and $\underline{r}$ and $\overline{r}$ are vectors with the minimum and maximum releases respectively.

The principle of dynamic programming as illustrated in Figure (C.1), states that the optimal solution is achieved when the sum of the immediate (f_t) and benefit-to-go functions (F_{t+1}) is maximum. As the volume of water left in storage at the end of stage t increases in a reservoir, the benefit-to-go function (F_{t+1}) increases as more water is available for future use. Conversely, the immediate benefits decrease as less water is being used during the current

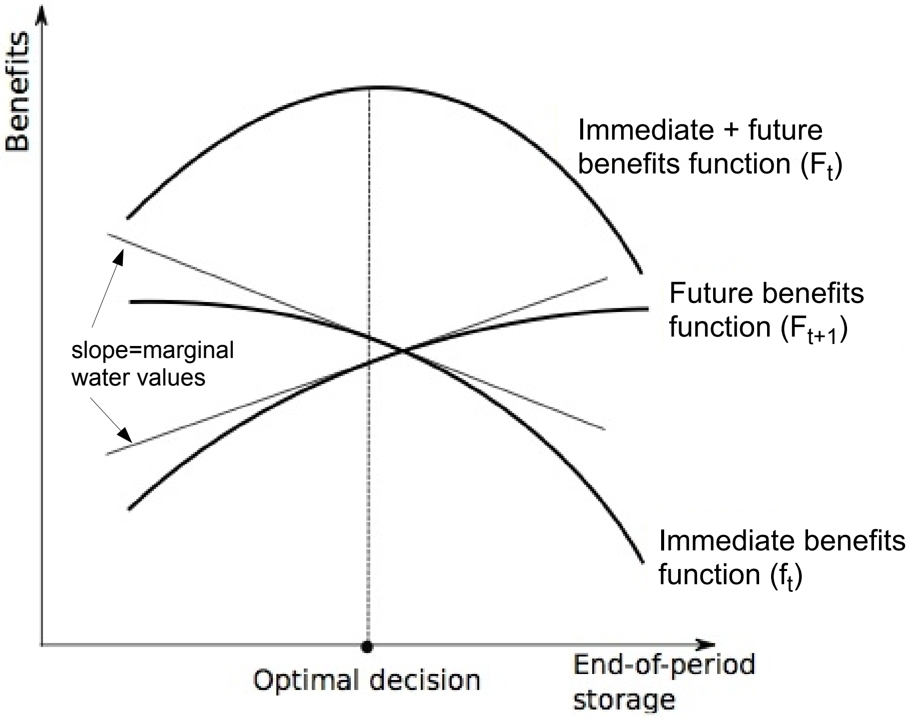

Figure C.1: Immediate and future benefit functions.

stage t. The derivatives of the immediate and benefit-to-go functions give the immediate and future water values respectively, which must be identical at the optimal solution.

The recursive equation (Equation C.3) is carried out until the change in the benefit-to-go function from one iteration to the next becomes nearly constant for each point of the discrete state space domain (Loucks et al., 2005). The resulting steady-state release policy and benefit-to-go functions constitute the set of solutions that can be used by reservoir operators to derive an optimal release policy. To solve the SDP model (Equation C.3), the hydrologic state variables as well as the storage variables must be discretized into N_q and N_s intervals respectively, each represented by a characteristic value (Yakowitz, 1982). The continuous domain (s_t, q_{t-1}) is, therefore, replaced by a grid so that an approximate solution of Equation C.3 can be developed by evaluating it at the grid points only. The drawback of this discrete approach comes from the fact that the computational effort (W) required to solve the SDP model increases exponentially with the number of reservoirs J $(W \propto (N_s N_q)^J)$, making it unsuitable to handle systems involving more than 3-4 reservoirs.

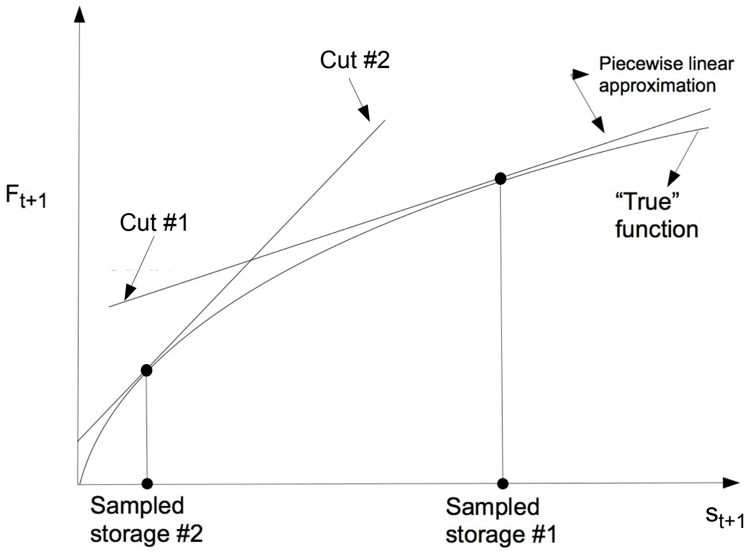

Figure C.2: Piecewise linear approximation of F_{t+1}.

C.3 Stochastic dual dynamic programming

Stochastic Dual Dynamic Programming (SDDP) is an extension of SDP that removes the computational burden that characterizes SDP by constructing a piecewise linear approximation of F_{t+1} through sampling and decomposition. For each sampled value of the state variable a hyperplane is constructed which provides an outer approximation of the benefit-to-go function F_{t+1}. This reduces the computational effort since the value of F_{t+1} can be derived through extrapolation instead of interpolation as in SDP. In other words, a limited number of values for the state variables (points) are now sufficient to provide an approximation of F_{t+1} as illustrated in Fig. (C.2).

To save further computation time the SDDP algorithm starts with a small number of points and then recursively constructs the cuts corresponding to these points starting at the last stage T and moving backward until the first stage t_0. The cuts generated during this backward optimization phase are then evaluated by checking whether the approximation they provide is statistically acceptable or not. This is done through forward simulations of the system with (1) the cuts generated in the previous backward optimization phases and (2) several hydrologic sequences, which can be historical and/or synthetically generated. If the approximation is not acceptable, then a new iteration starts and a new backward optimization phase is implemented with a larger sample which now also contains the points the last simulation went through.

Let φ^l_{t+1}, β^l_{t+1} and γ^l_{t+1} be the parameters of the l^{th} cut approximating F_{t+1}. The values of these parameters were determined previously, at stage $t+1$, from the primal and dual information available after having solved the one-stage optimization problem (Equation C.3) at that stage (Tilmant and Kelman, 2007). In SDDP, this one-stage optimization problem must be a convex program, such as a linear program (LP), so that the Kuhn-Tucker conditions for optimality are necessary and sufficient. In particular, the gradient of the objective function is equal to the linear combination of the gradients of the binding constraints and their corresponding dual information. It is therefore possible to evaluate the derivatives of the objective function F_{t+1} with respect to the state variables (s_{t+1}, q_t) from the derivatives of the binding constraints and the dual information, which are both available at the optimal solution at stage $t+1$. This analytical determination of the gradients of the functional equation F_{t+1} is explained below, but an important assumption regarding the structure of the immediate benefit function must first be introduced.

Since hydropower is a nonlinear function of the head (storage) and release variables, it cannot be used as such in the immediate benefit function of SDDP. One way to remove this source of non-convexity is to assume that the production of hydro-electricity is dominated by the release term and not by the head (or storage) term. With this linear assumption the one-stage optimization problem becomes a LP problem and the decomposition scheme can be implemented. Mathematically, the immediate benefit function (C.2) can be rewritten as:

$$f_t(s_t, r_t, q_t) = \tau_t \sum_j (\pi_t^h(j) - \theta(j)) c^h(j) r_t(j) - \xi_t^{'} x_t \tag{C.7}$$

where $c^h(j)$ is the production coefficient associated with the j^{th} hydropower plant (MW/m^{3}s^{-1}).

With the above immediate benefit function and using L cuts to approximate F_{t+1}, the one-stage optimization problem (C.3) becomes

$$F_t(s_t, q_{t-1}) = max \{f_t(s_t, q_t, g_t) + F_{t+1}\} \tag{C.8}$$

subject to:

$$s_{t+1} - C(r_t + l_t) = s_t + q_t - e_t(s_t) - i_t \tag{C.9}$$

$$\underline{s}_{t+1} \leq s_{t+1} \leq \overline{s}_{t+1} \tag{C.10}$$

$$\underline{r}_t \leq r_t \leq \overline{r}_t \tag{C.11}$$

$$f_t(s_t, r_t, q_t) = \tau_t \sum_j (\pi_t^h(j) - \theta(j)) c^h(j) r_t(j) - \xi_t^{'} x_t \tag{C.12}$$

$$\begin{cases} F_{t+1} - \varphi^1_{t+1} s_{t+1} \leq \gamma^1_{t+1} q_t + \beta^1_{t+1} \\ \vdots \\ F_{t+1} - \varphi^L_{t+1} s_{t+1} \leq \gamma^L_{t+1} q_t + \beta^L_{t+1} \end{cases} \tag{C.13}$$

A key step when developing a SDDP model is estimating the cut parameters φ^l_{t+1}, β^l_{t+1} and γ^l_{t+1}. These parameters are determined during the backward optimization phase and are then used in the forward simulation phase to check the quality of the approximation.

At stage $t+1$ the pair $(s^\circ_{t+1}, q^\circ_t)$ is sampled. From this pair, K vectors of inflows q^k_{t+1} are generated using the following autoregressive model of order one:

$$\begin{aligned} q_{t+1} = \mu_{t+1} \quad + \quad & \rho_{t+1,t} \frac{\sigma_{t+1}}{\sigma_t} \left(q^\circ_t - \mu_t \right) \\ & + \xi_t \sigma_t \sqrt{1 - \rho^2_{t+1,t}} \end{aligned} \tag{C.14}$$

where ρ, μ and σ are the estimated lag-one autocorrelation, mean and standard deviation associated with the inflows to the reservoirs. Note that residuals ξ_t are cross-correlated. The water balance constraint can then be calculated:

$$\begin{aligned} s_{t+2} \quad & - \quad C_R(r_{t+1} + l_{t+1}) \\ & = \quad s^\circ_{t+1} + q^k_{t+1} - e_{t+1}(s^\circ_{t+1}) - i_{t+1} \end{aligned} \tag{C.15}$$

and the corresponding dual information is $\lambda^{l,k}_{w,t+1}$, which is a $(J \times 1)$ vector, where J is the number of reservoirs. At stage $t+1$, the L cuts, which constitute the upper bounds to the true future benefits function F_{t+2}, are also constraints:

$$F_{t+2} - \varphi^l_{t+2} s_{t+2} \leq \gamma^l_{t+2} q_{t+1} + \beta^l_{t+2}, \quad l \in [1, \ldots, L] \tag{C.16}$$

and the dual information is the $(L \times 1)$ vector $\lambda^{l,k}_{c,t+1}$. The dual information of the optimization problem at stage $t+1$ can be used to derive the vector of slopes φ^l_{t+1} with respect to the storage state variable s_{t+1} to approximate the future benefit function F_{t+1} at stage t:

$$\frac{\partial F^k_{t+1}}{\partial s_{t+1}} = \lambda^{l,k}_{w,t+1} \tag{C.17}$$

Taking the expectation over the K artificially generated flows, the j^{th} element of the slope vector φ^l_{t+1} is:

$$\varphi_{t+1}^{l}(j) = \frac{1}{K}\sum_{k=1}^{K}\lambda_{w,t+1}^{l,k}(j) \tag{C.18}$$

Similarly, the j^{th} element of the vector of slopes γ_{t+1}^{l}, with respect to the hydrologic variable q_{t+1}, can be obtained from the dual information associated with the constraints (C.15) and (C.16), i.e. from the vectors $\lambda_{w,t+1}^{l,k}$ and $\lambda_{c,t+1}^{l,k}$ respectively:

$$\begin{aligned}
\frac{\partial F_{t+1}^{k}}{\partial q_t} &= \frac{\partial F_{t+1}^{k}}{\partial q_{t+1}}\frac{\partial q_{t+1}}{\partial q_t} \\
&= \left(\lambda_{w,t+1}^{l,k}(j) + \sum_{l=1}^{L}\lambda_{c,t+1}^{l,k}\gamma_{t+2}^{l}(j)\right) \\
&\times \left(\frac{\sigma_{t+1}(j)}{\sigma_t(j)}\rho_{t,t+1}(j)\right) \\
&= \gamma_{t+1}^{l,k}(j)
\end{aligned} \tag{C.19}$$

The expected slope with respect to the inflows can then be determined as:

$$\gamma_{t+1}^{l}(j) = \frac{1}{K}\sum_{k=1}^{K}\gamma_{t+1}^{l,k}(j) \tag{C.20}$$

Finally, the j^{th} element of the vector constant terms is given by:

$$\begin{aligned}
\beta_{t+1}^{l}(j) &= \frac{1}{K}\sum_{k=1}^{K}F_{t+1}^{k} \\
&- \varphi_{t+1}^{l}(j)\ s_{t+1}^{\circ}(j) - \gamma_{t+1}^{l}(j)q_t^{\circ}(j)
\end{aligned} \tag{C.21}$$

The objective function of the SDDP model, as defined in Equation C.8, does not include the economic benefits associated with irrigation. For details on the inclusion of irrigation into the model, refer to Tilmant, Pinte and Goor (2008).